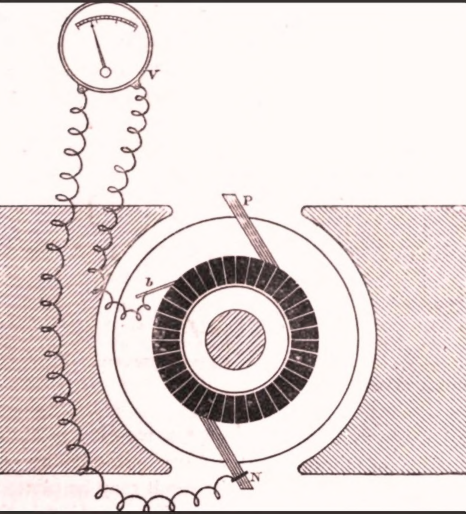


Dynamo-electric machinery

Silvanus Phillips Thompson

LAWI

Finsbury Technical Manuals

EDITOR OF THE SERIES

PROFESSOR SILVANUS P. THOMPSON

D.Sc., B.A., F.R.S., M.I.E.E., &c.

DYNAMO-ELECTRIC MACHINERY

A MANUAL
FOR STUDENTS OF ELECTROTECHNICS

BY

SILVANUS P. THOMPSON, D.Sc. B.A. F.R.S.

PRINCIPAL OF, AND PROFESSOR OF PHYSICS IN,
THE CITY AND GUILDS OF LONDON TECHNICAL COLLEGE, FINSBURY
LATE PROFESSOR OF EXPERIMENTAL PHYSICS IN UNIVERSITY COLLEGE, BRISTOL
MEMBER OF THE INSTITUTION OF ELECTRICAL ENGINEERS

FIFTH EDITION, REVISED

London:
E. & F. N. SPON, 125 STRAND
New York:
SPON & CHAMBERLAIN, 12 CORTLANDT STREET
1896

PREFACE

TO

THE FIFTH EDITION

SINCE 1892, when the fourth edition of this work appeared, much has been done in the development of the subject, chiefly in the domain of Alternate-current Machinery. To make room for the newer matter the earlier part of the book has been considerably compressed. Much of the chapter relating to the Magnetic Properties of Iron has been transferred to the author's work on *The Electromagnet.* The chapter on Alternators has been rewritten, as has that on Transformers. The subject of Alternate-current Motors has been divided into two parts, the first being now devoted to Synchronous Motors, the second to Asynchronous Motors: but the latter has been briefly handled, owing to the recent publication of the author's work on *Polyphase Electric Currents*, in which polyphase methods, both for generators and for motors, are discussed in detail. The subject of Motor-generators now constitutes a separate chapter.

In a department of applied science which has not only grown so rapidly but has become so highly specialised as this which deals with electric machinery, no single work can adequately treat of all branches. The author therefore refers the reader who desires to follow further any particular branch to the documents to which reference is made in footnotes throughout the book; and also to the books of Ewing on

Magnetic Properties of Iron; of Fleming on the Alternate-current Transformer; of Bedell and Crehore on Principles of Alternate Currents; of Kapp on Transformers, and on the Electric Transmission of Energy; of Weekes on the Design of Transformers; and of Du Bois on the Magnetic Circuit.

The author has again to acknowledge his indebtedness to various manufacturers and designers of machines for information and for material for preparing the various drawings. In particular he is under obligations to Messrs. Brown, Boveri and Co. (and to Mr. C. E. L. Brown); to the Oerlikon Maschinenfabrik (and to Mr. E. Kolben); to Messrs. Mather and Platt (and to Dr. E. Hopkinson); to Messrs. Johnson and Phillips; to Mr. H. F. Parshall, of the British Thomson-Houston Co., of London; to Mr. Thomas Parker, of Wolverhampton; to the Crocker-Wheeler Manufacturing Co., of Ampere, N.J.; to Mr. L. B. Stillwell and to Mr. R. Bellfield, of the Westinghouse Co.; to Hon. C. A. Parsons; to Messrs. Siemens and Halske; to the Allgemeine Elektrizitäts-Gesellschaft; to Messrs. Pyke and Harris; to Mr. W. M. Mordey, of the Brush Electrical Engineering Co.; to Mr. W. B. Sayers; and to other engineers too numerous to mention.

A special debt is also acknowledged to M. Boistel, who in translating into French the former edition of this work enriched it with supplementary notices of French forms of machines, of which the author has made use.

Lastly, the author acknowledges the untiring aid he has received throughout the revision from his assistant, Mr. Miles Walker.

S. P. T.

December 1895.

CONTENTS.

CHAPTER I.

PAGE

INTRODUCTORY 1

CHAPTER II.

HISTORICAL NOTES 5

CHAPTER III.

PHYSICAL THEORY OF DYNAMO-ELECTRIC MACHINES 22

CHAPTER IV.

ACTIONS AND REACTIONS IN THE ARMATURE 58

CHAPTER V.

MECHANICAL ACTIONS AND REACTIONS IN THE ARMATURE .. 96

CHAPTER VI.

MAGNETIC PRINCIPLES; AND THE MAGNETIC PROPERTIES OF IRON 112

CHAPTER VII.

THE MAGNETIC CIRCUIT 145

CHAPTER VIII.

PAGE

Forms of Field-Magnets 158

CHAPTER IX.

Elementary Theory of the Dynamo 168

CHAPTER X.

Characteristic Curves 196

CHAPTER XI.

Constant Potential Dynamos 224

CHAPTER XII.

Theory of Armature Winding 243

CHAPTER XIII.

Practical Construction of Armatures 284

CHAPTER XIV.

Commutators, Brushes and Brush-holders 312

CHAPTER XV.

Mechanical Points in Design and Construction 327

CHAPTER XVI.

Elements of Dynamo Design: Calculation of Windings 339

CHAPTER XVII.

Examples of Modern Dynamos (Continuous Current) .. 399

CHAPTER XVIII.

PAGE

ARC-LIGHTING DYNAMOS 445

CHAPTER XIX.

MISCELLANEOUS DYNAMOS 468

CHAPTER XX.

CONTINUOUS-CURRENT MOTORS 482

CHAPTER XXI.

MODERN FORMS OF CONTINUOUS-CURRENT MOTORS 531

CHAPTER XXII.

THE PRINCIPLES OF ALTERNATE CURRENTS 547

CHAPTER XXIII.

ALTERNATORS 579

CHAPTER XXIV.

SYNCHRONOUS ALTERNATE-CURRENT MOTORS 647

CHAPTER XXV.

ASYNCHRONOUS MOTORS (POLYPHASE AND MONOPHASE) .. 662

CHAPTER XXVI.

TRANSFORMERS 694

CHAPTER XXVII.

MOTOR-GENERATORS 724

CHAPTER XXVIII.

PAGE
Electric Transmission of Energy 732

CHAPTER XXIX.

Regulators for Dynamos 743

CHAPTER XXX.

Testing Dynamos and Motors 751

CHAPTER XXXI.

Management of Dynamos 765

APPENDIX A.

On Wires 779

APPENDIX B.

Numerical Statistics on Electro-Metallurgy 783

APPENDIX C.

Forms of Specification for Dynamos, Alternators, and Transformers 785

INDEX 793

LIST OF PLATES.

SUBJECT		DESCRIBED AT PAGE
I.	Kapp Dynamo: (Field-Magnets and Transverse Section of Armature)	403
II.	,, ,, (Armature in Longitudinal Section)	357
III.	,, ,, (Rocker, Brush-Holder, and Lubricator)	324
IV.	Brown's 2-Pole Dynamo (Oerlikon Company)	408
V.	Edison Bipolar Dynamos (General Electric Company)	428
VI.	Brown's 4-Pole Vertical-Shaft Exciter	415
VII.	,, Cylinder-wound Drum-Armature	310
VIII.	Berlin Dynamos (Siemens and Halske)	407
IX.	Electric Railway Plant (City and South London Subway)	424
X.	Street-Tramway 6-Pole Generator (Sectional Views)	434
XI.	Street-Tramway 6-Pole Generator (Commutator of)	434
XII.	Sayers' Generator for Power Transmission	438
XIII.	Small Brush Arc-Lighting Dynamo	451
XIV.	Mordey Alternator (Brush Electrical Engineering Company)	622
XV.	Parsons' Turbo-Alternator	625
XVI.	Brown's Design for Niagara Alternator	633
XVII.	,, Alternator (Frankfort Type)	635
XVIII.	,, Polyphase Motor	673
XIX.	Johnson and Phillips Transformer	705

DYNAMO-ELECTRIC MACHINERY.

CHAPTER I.

INTRODUCTORY.

A dynamo-electric machine is a machine for converting energy in the form of mechanical power into energy in the form of electric currents, or vice ver , by magneto-electric induction; the operation being in general that of setting conductors (usually of copper) *to rotate in a magnetic field.* This definition is framed to include all machines, the action of which is dependent on the principle of *induction*,[1] discovered by Faraday in 1831.

Every dynamo-electric machine is, however, capable of serving two distinct functions, the converse of one another. When supplied with mechanical power from some external source of power, such as a steam-engine, it furnishes electric currents. When supplied with electric currents from some external source such as a voltaic battery, it furnishes mechanical power. On the one hand the dynamo serves as a

[1] *Induction* means the inducing of electromotive force. The term originated with Faraday himself.

"Then I found that magnets would *induce* just like voltaic currents, and by bringing helices and wires and jackets up to the poles of magnets, electrical currents were *induced* in them . . . . . These two kinds of *induction* I have distinguished by the term volta-electric and magneto-electric *induction*."—Faraday to R. Phillips, Nov. 1831.

Though Faraday thus fixed the meaning of the term as the *operation* of inducing, a number of recent writers, including Hopkinson, have followed the unfortunate example set by Maxwell in using the term induction in a different sense to mean the density of the magnetic flux. This ought to be avoided.

generator, on the other hand as a *motor*. All dynamos, however, belong to one of two great subdivisions, being distinguished, according to the nature of the current which they are to supply, whether *continuous* (*i. e.* uni-directional in flow) or *alternating* (*i. e.* rapidly reversing the direction of the flow). We shall therefore have to consider four classes of machines—(*a*) continuous-current dynamos; (*b*) alternate-current dynamos, or, briefly, alternators; (*c*) continuous-current motors; (*d*) alternate-current motors. In the case of alternate-current machines, there is a further subdivision of classes into those which work with single-phase currents, and those which work with two or three currents in different phases. In general every dynamo, whether intended for use as a generator or as motor, consists of two essential parts, a *field-magnet*, usually a massive, stationary structure of iron surrounded by coils of insulated copper wire, and an *armature*, a peculiarly arranged system of copper conductors, usually wound upon the periphery of a ring, drum, or disk, fixed upon a shaft whereby rotation can be imparted mechanically. There are also special devices for receiving the electric currents from the armature and imparting them to the electric circuit, or *vice versâ*, known as *collectors* or *commutators*, attached to the armature and rotating with it, and collecting *brushes*, constituting sliding circuit-connexions, which press upon the moving surface of the collector or commutator. In those cases where the collecting brush slides from one piece of metal to another, thereby changing the connexions of the circuits, the revolving part is known as the *commutator*. In those cases where there is no change of connexions, but merely sliding contact with one and the same piece of metal, the parts are known as *slip-rings* or *collecting-rings*.

The function of the field-magnet is to provide a *magnetic field* of great extent and density; that is to say, to provide a great flux of lines of magnetic force through the space wherein the armature conductors are to revolve. It must consequently consist of a large and well-designed, and therefore powerful, magnet or electromagnet, having its poles so shaped that the magnetic lines that issue from them shall be

utilised in the armature space. The magnetic field and the magnetic properties of iron are dealt with in Chapter VI.; the fundamental principles of the magnetic circuit, including the designing of field-magnets, are dealt with in Chapters VII., VIII. and XVI.

The function of the armature is to rotate in the magnetic field, whilst carrying electric currents in its copper coils or conductors; and, while so rotating, to generate electromotive forces by the operation of "cutting" the magnetic lines. In many modern alternate-current generators the armature is stationary, whilst the magnet revolves. That part ought to be called the armature, which, whether revolving or stationary, is connected to the mains, giving current to them when the machine is used as a generator, or receiving current from them when used as a motor.

It must be remembered that there is a twofold action between a conducting wire (forming part of a circuit) and a magnetic field. *Firstly*, if the conducting wire is forcibly moved across the magnetic field (so as to cut across the magnetic lines), electric currents are generated in the conductor, and a mechanical effort is required to move the conductor. This is the action discovered by Faraday and termed "magneto-electric induction." In every case the induction or generation of currents necessitates the application of mechanical power and the expenditure of energy. This is the principle of the dynamo used as a generator. *Secondly*, if the conducting wire, while situated in the magnetic field, is actually conveying an electric current (from whatever source) it experiences a lateral thrust, tending to move it forcibly, parallel to itself, across the magnetic lines, and so enables it to exert force and to do work. This action, which is the converse of the former, is the principle of the dynamo used as a motor. In the first case power is required to drive the armature; in the second, the armature rotating becomes a source of power. If we have the magnetic field, and supply power to drive the rotating conductor, we get the electric currents; if we have the magnetic field and supply the electric currents to the conductor, it rotates and furnishes

power. Whether the machine be used as generator or as motor, the magnetic field must be present: hence the fundamental consideration in theory is the theory of the magnetic field. As every dynamo will work (at least theoretically) either as generator or as motor, it should be possible to frame a general theory for any machine serving either of these two converse functions. For the sake of simplicity, however, these two functions will be separately considered in the present work.

The mathematical theory of the dynamo is, indeed, complex, and takes different forms for its expression in the various classes of machine now included under the one name of "dynamo." The progress recently made in the theoretical treatment of magnetic problems has simplified matters so much that it is now possible to predict from the construction and dimensions of a dynamo its electrical output under given conditions of speed and load. The theory of alternate-current machines is different in many points from that of machines which are to furnish continuous currents. The theory of the dynamo, then, which will be developed in the present work, will not be a general mathematical theory. The aim will be to deal with physical and experimental rather than mathematical ideas, though of necessity mathematical symbols must be used here as in every kind of engineering work. A physical theory of the dynamo is not new, though none of any great completeness had been given[1] prior to the appearance of the author's lectures at the *Society of Arts* in 1882.

Before, however, proceeding to the general theory of the dynamo, it will be expedient to introduce a few historical notes.

[1] See J. M. Gaugain, *Annales de Chimie et de Physique*, 1873; Antoine Breguet, *Annales de Chimie et de Physique*, 1879; Du Moncel, *Exposé des Applications de l'Electricité*, vol. ii.; Niaudet, *Machines Électriques*; Dredge's *Electric Illumination*; Schellen, *Die Magneto- und Dynamo-elektrischen Maschinen* (3rd edition, 1883).

CHAPTER II.

HISTORICAL NOTES.

FARADAY'S discovery of the magneto-electric induction of currents was made in the autumn of 1831, and communicated, on Nov. 24th, to the Royal Society in a paper printed in the *Philosophical Transactions*, and reprinted in the beginning of the first volume of Faraday's *Experimental Researches in Electricity*. His first experiments related to the production of induced currents in a coil by means of currents started or stopped in a neighbouring coil; from these he went on to currents generated in a coil moved in front of the poles of a powerful steel magnet. Upon thus obtaining electricity from magnets he attempted to construct "a new electrical machine." A disk of copper, 12 inches in diameter (Fig. 1), and about one-fifth of an inch in thickness, fixed upon a brass axle, was mounted in frames, so as to allow of revolution, its edge being at the same time introduced between the magnetic poles of a large compound permanent magnet, the poles being about half an inch apart.[1] The edge of the plate was well amalgamated, for the purpose of obtaining a good but movable contact, and a part round the axle was also prepared in a similar manner. Conducting strips of copper and lead, to serve as electric collectors, were prepared, so as to be placed in contact with the edge of the copper disk; one of these was held by hand to touch the edge of the disk between the magnet poles. The wires from a galvanometer were connected, the one to the collecting-strip, the other to the brass axle; then on revolving the disk a deflexion of the galvanometer was obtained, which was reversed in direction when the direction of the rotation

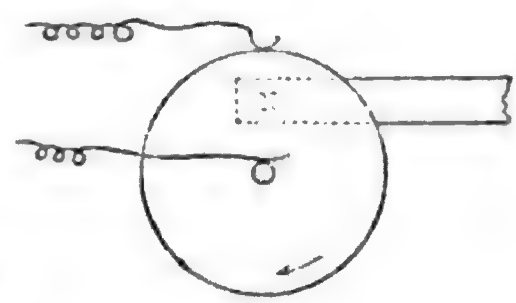


FIG. 1.
FARADAY'S DISK DYNAMO.

[1] *Experimental Researches*, i. 25, art. 85. This piece of apparatus is still preserved at the *Royal Institution*. It was shown in action by the author of this work, at a lecture at the Royal Institution delivered April 11th, 1891.

was reversed. "Here, therefore, was demonstrated the production of a permanent current of electricity by ordinary magnets." These effects were also obtained from the poles of electromagnets, and from copper helices without iron cores. Several other forms of magneto-electric machines were tried by Faraday.

In one,[1] a flat ring of twelve inches external diameter, and one inch broad, was cut from a thick copper plate, and mounted to revolve between the poles of the magnet, two conductors being applied to make rubbing contact at the inner and outer edge at the part which passed between the magnetic poles. In another,[2] a disk of copper, one-fifth of an inch thick and only 1½ inch in diameter (Fig. 2), was amalgamated at the edge, and mounted on a copper axle. A square piece of sheet metal had a circular hole cut in it, into which the disk

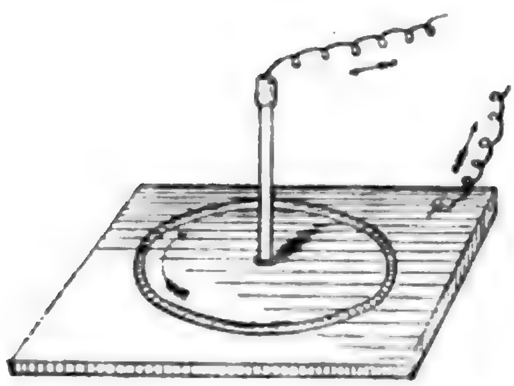


FIG. 2.—FARADAY'S TEETOTUM APPARATUS.

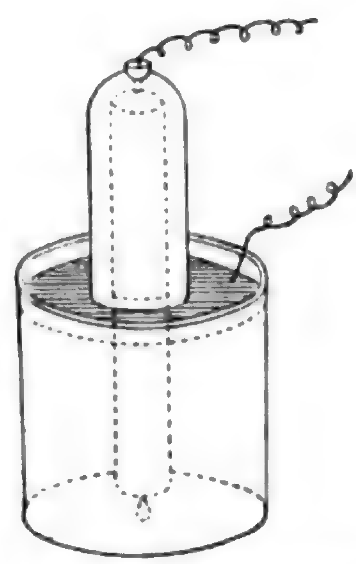


FIG. 3.—FARADAY'S ROTATING COPPER CYLINDER.

fitted loosely, a little mercury completed communication between the disk and its surrounding ring. The latter was connected by wire to a galvanometer; the other wire being connected from the instrument to the end of the axle. Upon rotating the disk in a horizontal plane, currents were obtained though the earth was the only magnet employed.

Faraday also proposed a multiple machine[3] having several disks, metallically connected alternately at edges and centres by means of mercury, which were then to be revolved alternately in opposite directions. In another apparatus[4] a copper cylinder (Fig. 3), closed at one extremity, was put over a magnet, one half of which it enclosed

[1] *Experimental Researches*, i. art. 135.
[2] *Ib.*, art. 155.
[3] *Ib.*, art. 158.
[4] *Ib.*, art. 219.

like a cap, and to which it was attached without making metallic contact. The arrangement was then floated upright in a narrow jar of mercury, so that the lower edge of the copper cap touched the fluid. On rotating the magnet and its attached cap, a current was sent through wires from the mercury to the top of the copper cap. In another apparatus,[1] still preserved at the Royal Institution, a cylindrical bar magnet, half immersed in mercury, was made to rotate, and generated a current, its own metal serving as a conductor. In another form,[2] the cylindrical magnet was rotated horizontally about its own axis, and was found to generate currents which flowed from the middle to the ends, or *vice versâ*, according to the rotation. In all these machines the operations were homopolar, and

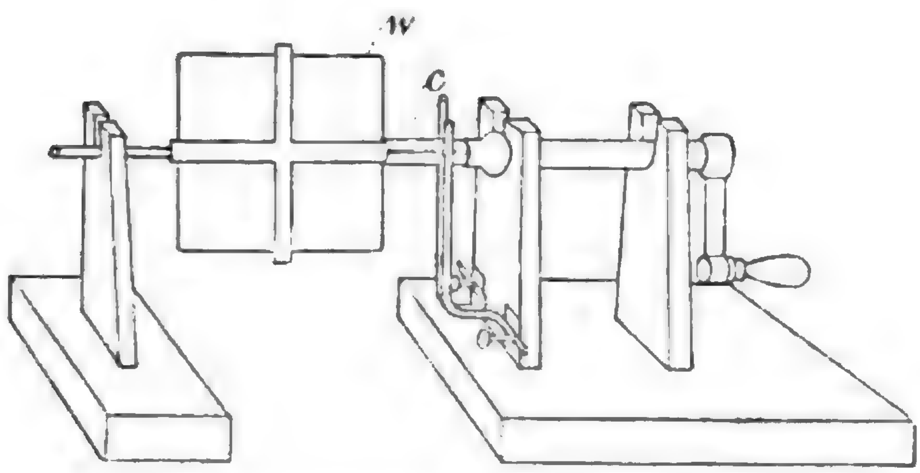


FIG. 4.—FARADAY'S ROTATING RECTANGLE.

the induction continuous; but in another machine (Fig. 4) constructed some time later,[3] the operation was heteropolar, and the induction alternate. Here a simple rectangle of copper wire, attached to a frame, was rotated about a horizontal axis placed east and west, and generated alternate currents, which could be collected by a simple commutator.

Within a few months machines on the principle of magneto-induction had been devised by Dal Negro,[4] and by Pixii.[5] In the latter's apparatus a steel horseshoe magnet, with its poles upwards, was caused to rotate about a vertical shaft, inducing alternate currents in a pair of bobbins fixed above it, and provided with a horseshoe core of soft iron. Later, in 1832, Pixii produced, at the

[1] *Experimental Researches*, i. art. 220.
[2] *Ib.*, art. 222. [3] *Ib.*, iii. art. 3192.
[4] *Phil. Mag.* [3] i. 45, July 1832 (an oscillatory apparatus).
[5] *Ann. Chim. Phys.*, l. 322, 1832.

suggestion of Ampère,[1] a second machine, provided with commutators to rectify the alternating currents. Further improvements were made by Ritchie[2] and Watkins.[3] In 1833 appeared the machine of Saxton,[4] and two years later that of Clarke;[5] both having the steel horseshoe magnet a fixture, and having as a revolving armature an electromagnet consisting of a pair of bobbins wound upon a simple horseshoe of iron. Clarke's machine possessed many original details, including a special form of commutator for giving short, sharp currents for physiological purposes. In it the armature rotated, not opposite the ends, but in close proximity to the flat faces of the magnet. In Saxton's machine, which was shown to the British Association at Cambridge in 1833, the armature was rotated opposite the polar ends, and consisted of four coils. Von Ettingshausen,[6] in 1837, brought out a very similar alternate-current machine, with a special device by which the alternate currents could be cut out. Poggendorff,[7] in 1838, devised a special mercury-cup commutator for Saxton's machine, to make the currents less discontinuous.

Other improvements in detail were made by Petrina,[8] who improved the commutator; Jacobi,[9] who pointed out the importance of using short cores for the armatures; Sturgeon,[10] who placed a shuttle-wound coil longitudinally between the limbs of a horseshoe magnet, and who also invented the simple two-part commutator or "unio-directive discharger," as he termed it; Stöhrer,[11] who showed how to construct a six-pole machine with six bobbins in the armature; Ritchie,[12] who employed tubular cores and a double winding; and Pulvermacher,[13] who in 1849 proposed the use of thin laminæ of iron as core-plates. Woolrich,[14] in 1841, devised a multipolar machine

[1] *Ann. Chim. Phys.*, li. 76, 1832.

[2] *Phil. Mag.* [3] viii. 455; [3] x. 280, 1837; and *Phil. Trans.*, ii. 318, 1833.

[3] *Phil. Mag.* [3] vii. 107, 1835.

[4] *Phil. Mag.* [3] ix. 360, 1836.

[5] *Phil. Mag.* [3] ix. 262, 1836; x. 365, 455, 1837; and Sturgeon's *Annals of Electricity*, i. 145.

[6] Gehler's *Physikalisches Wörterbuch*, ix. 122, 1838.

[7] *Pogg. Ann.*, xlv. 385, 1838.

[8] *Pogg. Ann.*, lxiv. 58, 1845.

[9] *Pogg. Ann.*, lxix. 194, 1846.

[10] *Annals of Electricity*, ii. 1, 1838. See, also Sturgeon's *Scientific Researches*, p. 252; also *Phil. Mag.*, vii. 231, 1835.

[11] *Pogg. Ann.*, lxi. 417, 1884; lxxvii. 467, 1849.

[12] Specification of Patent, 14,899 of 1849.

[13] *Loc. cit.*

[14] See also Specification of Patent, 9431 of 1842.

for electroplating, having twice as many rotating coils as magnet-poles. Wheatstone[1] began his improvements in 1841, with a machine in which for the first time the armature coils were so grouped as to give a really continuous current (Fig. 5). For this purpose five armatures, each consisting of a pair of short parallel cylindrical coils with iron cores, and each having a simple split-tube commutator, were arranged in a row along a single shaft, with six compound steel magnets between them, the five armatures being so set that they came successively into the position of

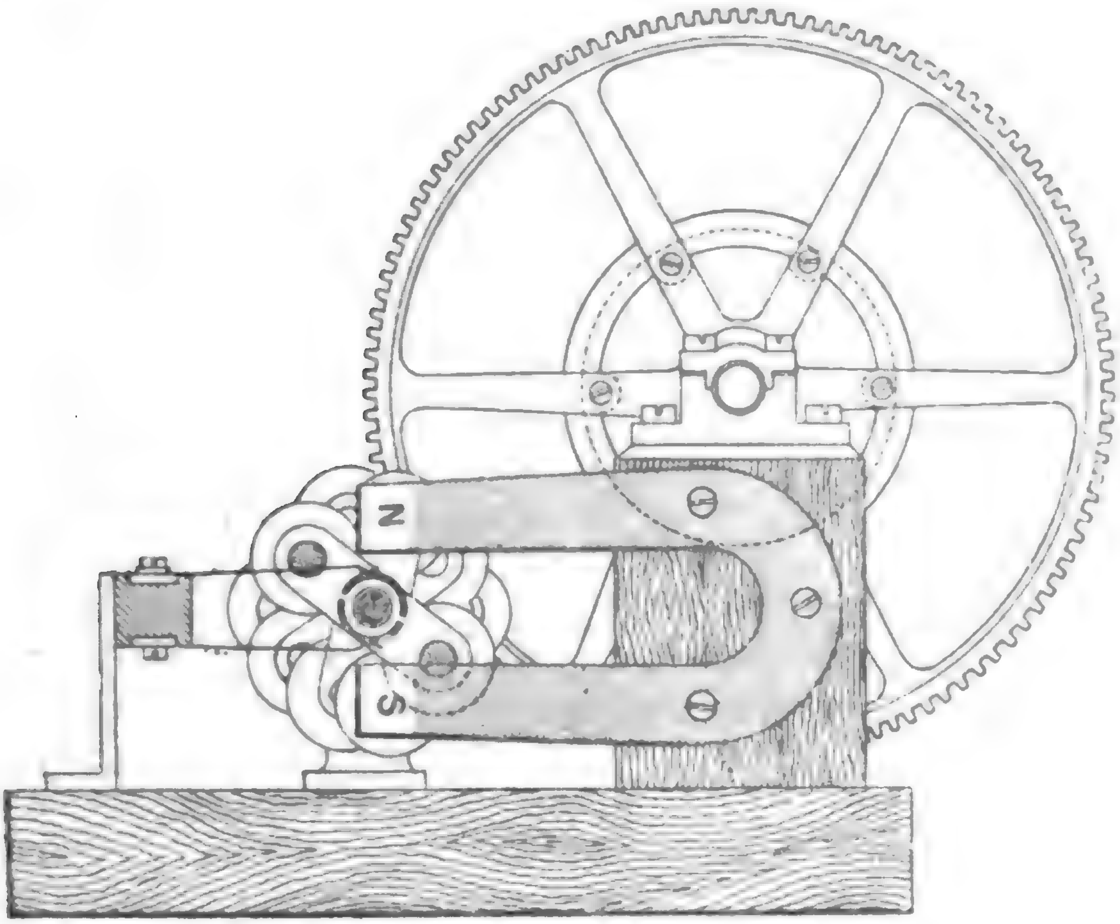


FIG. 5.—WHEATSTONE'S CONTINUOUS-CURRENT MACHINE.

greatest activity, no two of them being commuted at the same instant. They were connected in series with one another by wires, which joined the positive brush—a brass spring—of one to the negative brush of the next. In 1845 Wheatstone[2] and Cooke patented the use of electromagnets instead of steel permanent magnets in such machines. In 1848 Jacob Brett[3] made the important suggestion of causing the current developed in the armature by

[1] Specification of Patent, 9022 of 1841.
[2] Specification of Patent, 10,655 of 1845.
[3] Specification of Patent, 12,054 of 1848.

the permanent magnetism of the field-magnets to be transmitted through a coil of wire surrounding the magnet, so as to increase its action. This suggestion, which appears to be the first indication of the principle of the self-exciting dynamo, was independently made in 1851 by Sinsteden,[1] who appears to have had full knowledge of the fact, investigated by Müller, that steel is capable of receiving a temporary magnetization not greatly inferior to that of wrought iron, and far in excess of that which it can permanently retain. Sinsteden's researches were numerous and important, relating to the best width of polar surface to employ, to the use of pole-pieces, and to the lamination of armature cores, for which purpose he employed, in 1849, iron wire bundles. A quite different type of machine was suggested independently by Ritchie,[2] by Page,[3] and by Dujardin,[4] in which neither field-magnet nor armature rotated; the coils in which the currents were to be induced were wound upon polar extensions of the field-magnets, and the induction was produced by rotating in front of them pieces of soft iron, which set up rapid periodic variations in the magnetic field. Machines on this "inductor" principle were later devised by Holmes, Henley, Wheatstone, Wilde, Sawyer, by the author of this work, and by Kingdon.

Nollet,[5] in 1849, devised an alternate-current machine, in the construction of which he was joined by Van Malderen; and after the death of Nollet this was developed, with the aid, first of Holmes, then of Masson and Du Moncel, into the "Alliance"[6] machine which, from the year 1863, did good service in the lighthouses of France. Holmes continued to perfect his work, and produced a fine machine,[7] which in 1857 received high commendation from Faraday. The great machine of Holmes shown in the International Exhibition of 1862, was a continuous-current machine, with a large commutator and rotating rollers for brushes; the bobbins, 160 in number, were arranged on the peripheries of two wheels, each about

[1] *Pogg. Ann.*, lxxxiv. 186, 1851. For Sinsteden's other researches see *Pogg. Ann.*, lxxvi. 29, 195 and 524, 1849; lxxxiv. 181, 1852; xcii. 1 and 220, 1854; xcvi. 353, 1855; cxxxvii. 290 and 483, 1869.

[2] *Phil. Mag.* [3] x. 280, 1837.

[3] *Annals of Electricity*, 489, 1839.

[4] *Comptes Rendus*, xviii. 837, 1844; xxi. 528, 892, 1881.

[5] See Specification of Patent, 13,302 of 1850. See also Douglass in *Proc. Inst. Civil Engin.*, lvii. 1878–9.

[6] See Du Moncel's *Exposé des Applications de l'Électricité*, i. 361. Also see Le Roux, *Bulletin de la Société d'Encouragement*, 1868.

[7] See Douglass, *loc. cit.* Also Specifications of Patents, 573 of 1856, 2060 of 1868, and 1774 of 1869.

9 feet in diameter. There were sixty horseshoe magnets arranged in three circles, each presenting radially forty poles. In 1867 Holmes remodelled his machine, making the field-magnets more powerful in proportion, and leaving the induced currents uncommuted; and in 1869 he introduced the principle of diverting the current from a few of the armature coils, through a commutator, to excite the field-magnets. This period was one of great activity. In 1855 Hjorth [1] patented a remarkable machine, having for its field-magnets a compound arrangement of a permanent magnet to provide initial currents, and powerful electromagnets to be excited up by the currents generated by the machine itself.

C. W. Siemens [2] in 1856 provisionally patented the famous shuttle-wound longitudinal armature, invented by Werner Siemens. In 1859,[3] he made the suggestion that the core only need rotate, the coils being fixed in grooves in the pole-pieces of the field-magnets. Wilde,[4] of Manchester, embarked on a remarkable series of researches from 1861 to 1867. Beginning with small apparatus for telegraphic purposes, he was led in 1863 to devise an apparatus having a shuttle-wound Siemens armature between the poles of a powerful electromagnet, the coils of which were traversed by currents furnished by a small auxiliary machine—with shuttle-wound armature and permanent magnets—mounted upon its summit. In 1866 and 1867 Wilde devised alternate-current machines, of which the latest had a number of bobbins mounted on the periphery of a disk rotating between two opposite crowns of alternately polarized field-magnets—a type which survives to the present day. These machines, originally separately excited by currents from a small magneto machine, were made self-exciting, in 1873, by diverting through a commutator the currents induced in one or more of the armature bobbins. The principle of using the whole or part of the machine's own currents to excite the requisite magnetism of its field-magnets was by this time becoming recognised. As mentioned above, Brett, Sinsteden, and Hjorth had all made use of this principle. In 1858, Johnson,[5] patent agent for a foreign inventor, states; "It is proposed to employ the electromagnet in obtaining induced electricity, which

[1] Specifications of Patents, 12,295 of 1848, 2199 of 1854, 2198 of 1854, 806 of 1855, 807 of 1855, and 808 of 1855.

[2] Specification of Patent, 2017 of 1856. See W. Siemens, *Pog. Ann.*, ci. 271, 1857.

[3] Specification of Patent, 512 of 1859.

[4] Specifications of Patents, 299, 858, 1994 and 2997 of 1861; 516 and 3006 of 1863, 1412 and 2753 of 1865, 3209 of 1866, and 824 of 1867.

[5] Specification of Patent, 2670 of 1858.

supplies wholly or partially the electricity necessary for polarizing the electromagnets, which electricity would otherwise be required to be obtained from batteries or other known sources." In July 1866, Murray[1] stated that he had connected in series with the armature some coils wound on the field-magnets of his magneto machine and recommended the adoption of this plan. In October 1866, Moses G. Farmer[2] wrote to Wilde of Manchester, describing his success in winding main circuit coils upon the field magnets of his machine, so as to cause it to excite its own magnets. In November 1866, Baker[3] stated that the secondary currents from the revolving magnets might be applied to magnetize the fixed magnets. In December of the same year C. and S. A. Varley[4] filed a Provisional Specification for a machine having electromagnets only, which apparatus, however, required before using to have given to it a small amount of permanent magnetism since the inventors state that "the bobbins become slightly magnetized in their passage between the poles of the permanent magnets." This, it must be conjectured, was given to it by passing an electric current through the coils of the electromagnets; a device which reappears in another machine patented by the same inventors in June 1867, and again in another by O. and F. H. Varley in 1869. The electromagnets of the 1867 machine were wound with two separate circuits, supplied alternately with currents from two commutators which received the currents from two separate pairs of coils. Mr. S. A. Varley continued, in 1868 and 1871, to patent magneto-electric generators. In 1876 he returned to the self-exciting method, employing a multiple armature in which the principle was applied of cutting out each coil in succession during the rotation. In this machine also there were two windings on the field-magnets, one of greater resistance than the other, both of which were led to the lamp, the circuit of greater resistance being always closed. It was not, however, clear that this method of double winding was what is now understood as "compound winding,"[5] until such was laid down with legal authority by a Scotch judge fifteen years later. Returning to the self-exciting principle, we find that on January 17th, 1867,

[1] See *Engineer*, p. 42, July 20, 1866.

[2] *Proc. Lit. and Phil. Soc. of Manchester*, vi. 107.

[3] Specification of Patent, 3039 of 1866.

[4] Specification of Patent, 3394 of 1866. Other Varley Specifications are 1755 of 1867, 315 of 1868, 131 and 1150 of 1871, 4905 of 1876, 270 and 4435 of 1877, 4100 of 1878.

[5] See *Phil. Mag.* [4] xlv. 439, 1873.

Dr. Werner Siemens [1] described to the Berlin Academy a machine for generating electric currents by the application of mechanical power, the currents being induced in the coils of a rotating armature by the action of electromagnets, which were themselves excited by the currents so generated. In this machine also initial permanent magnetism was to be given by sending a preliminary current through the coils from a battery. To mark the importance of this departure Siemens coined the name *dynamo-electric machine*, which now, in the shortened form of *dynamo*, has become the familiar term for all these electric machines driven by mechanical power, whether self-excited or

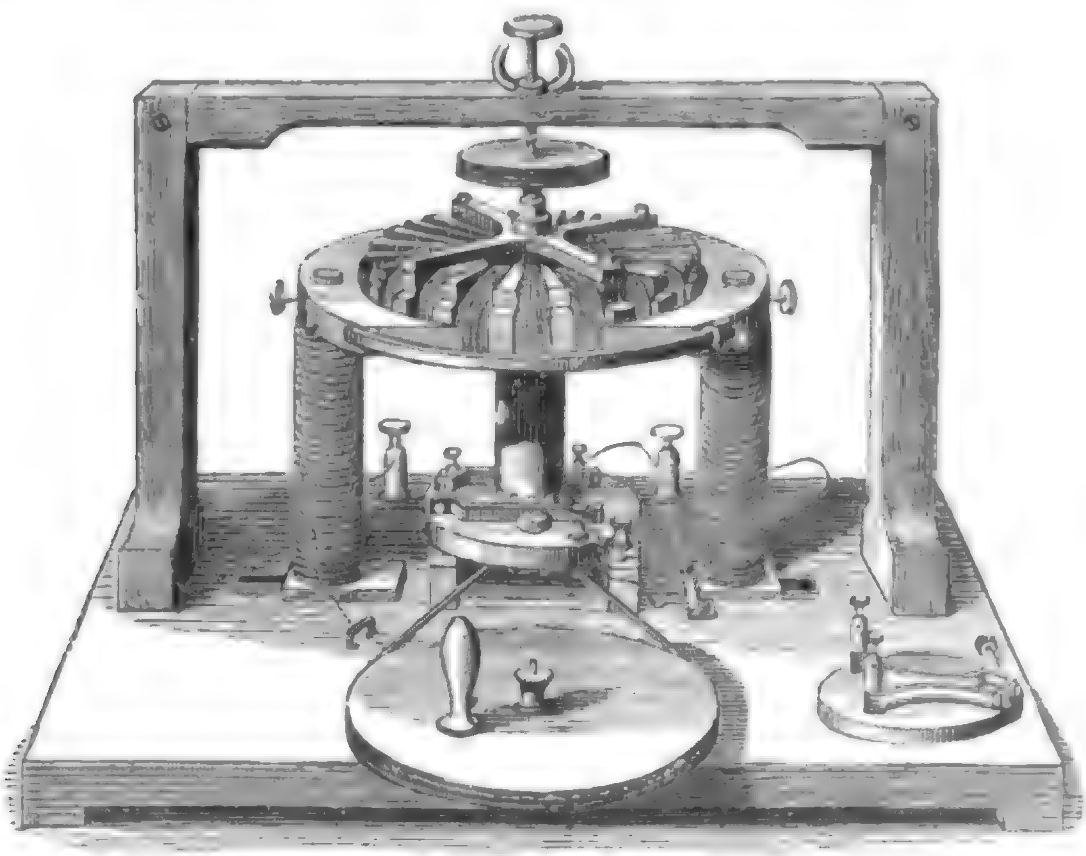


FIG. 6.—PACINOTTI'S MACHINE, WITH RING ARMATURE.

not. On the same day that this discovery was announced to the Royal Society, February 14th, 1867, a paper was read by Sir C. Wheatstone,[2] making an almost identical suggestion; but with this difference, that whilst Siemens proposed that the exciting coils should be in the main circuit, in series with the armature coils, Wheatstone proposed that they should be connected as a shunt. A self-exciting machine without permanent magnets had indeed been constructed for Wheatstone by Mr. Stroh in the summer of 1866.

[1] *Berliner Berichte*, Jan. 1867; *Proc. Roy. Soc.*, Feb. 14, 1867; Specification of Patent, 261 of 1867; and *Pogg. Ann.*, cxxx. 332, 1867.

[2] *Proc. Roy. Soc.*, Feb. 14, 1867.

In 1867 Ladd[1] exhibited a self-exciting machine having two shuttle-wound armatures, a small one to excite the common field-magnet, a large one to supply currents for electric light.

Meantime the question of procuring continuous currents, with less fluctuation in their strength, had come up, and had received from Pacinotti[2] an answer which, though it fell into temporary oblivion, is now recognized as of great merit. He devised a machine, first described in 1864, having as its armature an electromagnet in the form

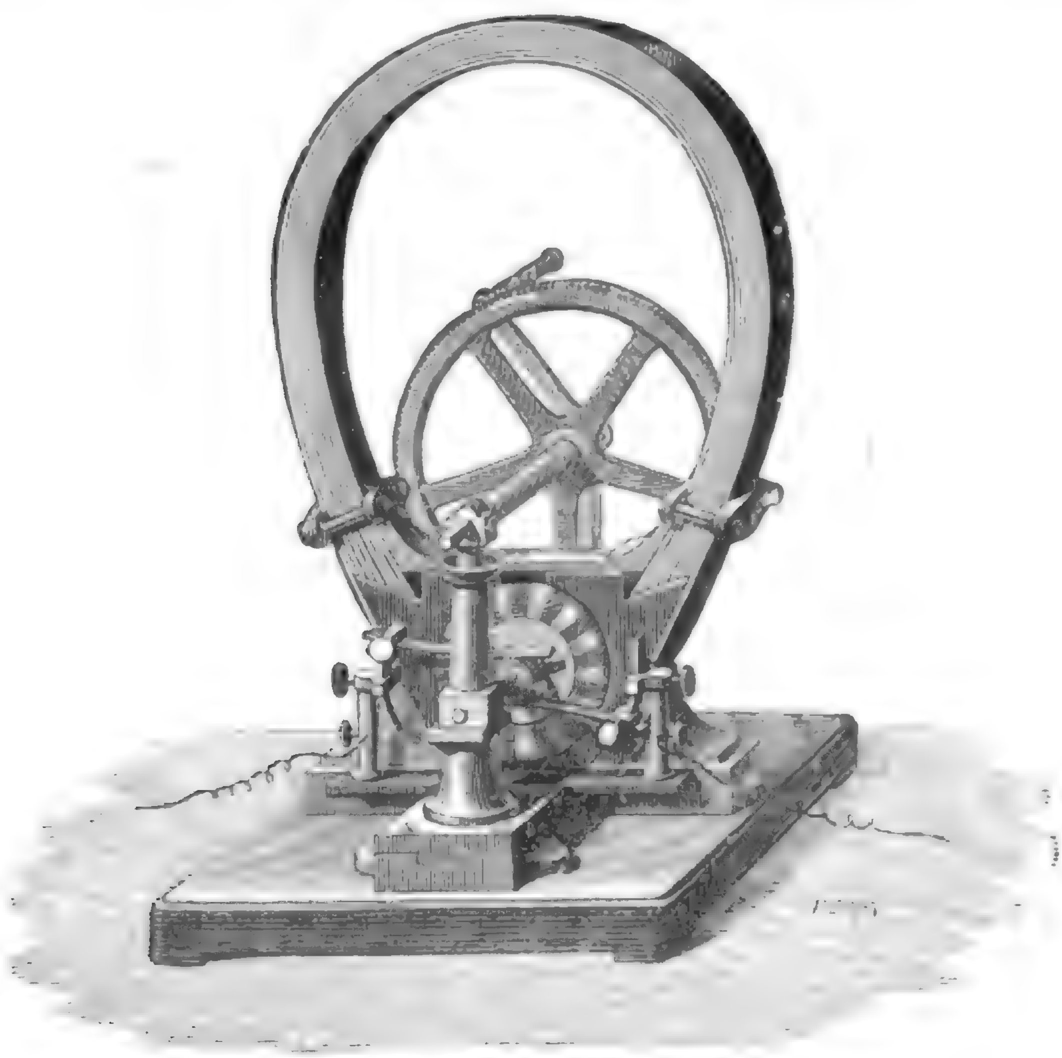


FIG. 7.—GRAMME MACHINE, LABORATORY PATTERN.

of a ring, the core consisting of a toothed iron wheel, between the teeth of which the coils were wound in sixteen separate sections. He denominated this a "transversal electromagnet." The coils being joined up in a closed circuit, if at any point a current was introduced, it flowed both ways through the coils to some other point where it was taken off by a return wire. By the device of leading down connections, at sixteen different points around the ring, to sixteen insulated pieces of

[1] *Phil. Mag.* [4] xxxiii. 544, 1867. [2] *Nuovo Cimento*, xix. 378, 1865.

metal arranged as a commutator, it was possible to cause magnetic poles to appear in the ring at any desired points. The principle of winding a continuous coil in separate symmetrical sections around a ring, or other figure of revolution, was independently invented, in 1870, by Gramme,[1] whose ring had no teeth, and was entirely overwound with wire. By winding an armature with a number of such symmetrically grouped coils which pass successively through the magnetic field, currents can be obtained that are practically steady. The introduction of the Gramme armature was at once recognized as marking an important step, and it gave a fresh impetus to invention. In 1873

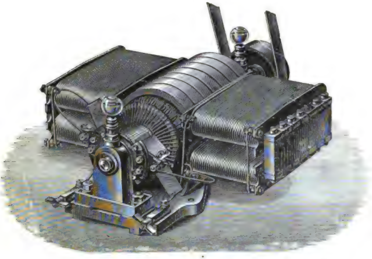


FIG. 8.—SIEMENS'S DYNAMO WITH VON HEFNER ALTENECK'S DRUM-WOUND ARMATURE.

von Hefner Alteneck[2] modified the longitudinal armature of Siemens by covering it with windings spaced out at symmetrical angles to secure the same advantage of continuity, and Lontin[3] in 1874 sought to perform a like transformation upon an armature with radiating poles. Gramme and Siemens both devised many special forms of

[1] *Comptes Rendus*, lxxiii. 175, 1871, and lxxv. 1497, 1872; and Specification of Patent, 1668 of 1870.

[2] Specification of Patent, 2006 of 1873. A similar suggestion had been thrown out the previous year by Worms de Romilly.

[3] Specifications of Patents, 473 of 1875, 386 and 3264 of 1876.

machines, some furnishing alternating currents,[1] others continuous currents. Bertin in 1875, Brush in 1879, and Siemens,[2] in 1880, revived the method of shunt-winding.

In 1878 Pacinotti[3] devised a kind of armature in which the conductors took the form of a flat disk or fly-wheel. Brush[4] also introduced his famous dynamo embodying the principle of open-coil working. He also introduced the simultaneous use of a shunt and a series winding for the purpose of enabling the machine to do either a large or a small amount of work. Another open-coil machine was introduced in 1880 by Elihu Thomson and E. J. Houston,[5] of Philadelphia. About the same time Weston[6] devised several forms of dynamo, and in particular developed shunt-wound machines. Many other American inventors produced dynamos, amongst them Edison,[7] who began in 1878, with a machine in which the motion was oscillatory instead of rotatory, a device which had been tried by Dujardin,[8] in 1856, by Siemens,[9] in 1859, by Wilde,[10] in 1861, and abandoned. Edison himself abandoned it in 1879 for a form of machine having a modified Hefner-Alteneck armature and an elongated shunt-wound electromagnet. In 1881 he produced a disk dynamo on the same lines as Pacinotti's disk. The same year saw a revival of alternate-current machines in the forms devised by Lord Kelvin[11] (and independently by Ferranti) and Gordon,[12] who constructed large two-phase generators.

About this time multipolar dynamos began to come into favour, the multipolar drum armature introduced by Lord Elphinstone[13] and Mr. Vincent, and the multipolar ring, independently, by Schuckert, Gramme, Gülcher, and Mordey.[14] Lord Elphinstone in particular drew attention to the importance of perfecting the magnetic circuit, though, for purely mechanical reasons, his machine soon became

[1] Specification of Patents, Gramme, 953 of 1878; Siemens, 3134 of 1878.

[2] *Phil. Trans.*, March 1880.

[3] *Nuovo Cimento* [3] i. 1881.

[4] Specification of Patent, 2003 of 1878.

[5] Specification of Patent, 315 of 1880.

[6] Specifications of Patents, 4280 of 1876, 1614 and 2194 of 1882.

[7] Specifications of Patents, 4226 of 1878, 2402 of 1879, 1240 and 2954 of 1881, and 2052 of 1882.

[8] See Du Moncel's *Exposé des Applications*, i. p. 372.

[9] Specification of Patent, 512 of 1859.

[10] Specification of Patent, 924 of 1861.

[11] Specification of Patent, 5668 of 1881.

[12] Specifications of Patents, 5536 of 1881 and 2871 of 1882.

[13] Specifications of Patents, 332 of 1879, and 2893 of 1880.

[14] Specification of Patent, 400 of 1883.

obsolete. Hopkinson [1] showed how greatly the performance of a dynamo was improved by improving and making more compact its magnetic circuit, whilst Crompton [2] amidst a number of improvements in detail, showed the advantage of increasing the cross-section of iron in the armature core. Meantime theoretical considerations had led Marcel Deprez,[3] in 1881, to the conclusion that a dynamo driven at a certain critical speed ought to be able to distribute currents at a constant potential if its field-magnets were provided with a second coil to furnish from a battery or other source an independent and constant auxiliary excitation. This was almost immediately followed by the general adoption of the so-called compound winding, for the purpose of obtaining a self regulating dynamo, this advance being the subject of conflicting rival claims. Since 1883 the chief progress made has been in details of design and mechanical construction. Large multipolar machines for continuous currents have been designed by Siemens and Halske, by C. E. L. Brown, and others, and are superseding bipolar forms. Disk dynamos have also been introduced by Desroziers and by Fritsche. Special methods of construction to facilitate the sparkless collection of large currents have been devised by Ryan and by W. B. Sayers. Large alternating machines have been constructed by various designers, Mordey's machine having a notable departure in the use of a single compact magnetic circuit for the field-magnet. Polyphase alternate-current generators have been introduced, chiefly since 1891, for the purpose of furnishing two or more alternate currents differing in phase from one another; the reason for these machines being the convenience of distributing power by alternate currents to polyphase motors. Quite recently there are signs of a revival of the "inductor" type of alternator, having no copper in the moving parts; Kingdon, Stanley, Brown, Dobrowolsky, Pyke and Thury having independently perfected such machines. The "umbrella" type of dynamo, with vertical driving shaft was introduced by Brown for turbine service, and has been used in many very large machines. The largest are the two-phase alternators in use at Niagara, constructed by the Westinghouse Co.

The other branch of the subject, that of the electric motor, goes back to the discovery by Faraday [4] in 1821 of electromagnetic

[1] Specification of Patent, 973 of 1883.
[2] Specifications of Patents, 2618 and 4810 of 1882, and 4302 of 1884.
[3] *La Lumière Électrique*, December 3 1881, and January 5, 1884.
[4] Journal of *Royal Institution*, September 1821.

rotation, and the invention, in 1823, by Barlow,[1] of his rotating wheel. The earliest electric motors in which the principle of attraction by an electromagnet was applied were those of Henry,[2] in 1831, and of Dal Negro,[3] in 1832, and these were followed in 1833 and 1834 by the motors of Ritchie[4] and of Jacobi,[5] and in 1837 by that of Davenport.[6] Many other inventors devised machines of this kind, some of the most famous being Page[7] in the United States, Davidson in Scotland, Wheatstone[8] in England, Froment[9] in France, and Pacinotti[10] in Italy. The discovery that the action of a dynamo is the simple converse of that of the motor, and that the same machine can serve either function, appears to have been made by Lenz,[11] in 1838. It was known to Jacobi[12] in 1850, though it only came into general recognition somewhat later. It was certainly known in 1852, for in the fourth edition of Davis's *Magnetism*, published at Boston, an apparatus, described as a "revolving electro-magnet" (a slight modification of Ritchie's motor) is shown, on page 212, as a motor, and the same apparatus is again shown on page 268 as a generator, accompanied by the remark that "any of the electromagnetic instruments in which motion is produced by the mutual action between a galvanic current and a steel magnet may be made to afford a magneto-electric current by producing the motion mechanically." Walenn[13] explicitly stated the same point in 1860; and it was also stated by Pacinotti in 1864. The principle of transmitting power from one dynamo used as a generator to another used as motor is claimed for Fontaine and Gramme, as a discovery made in 1873, when such an arrangement was shown at Vienna. It has been noisily claimed, but without the shadow of reason, for Marcel Deprez,[14] who did not, however, discover it until 1881. In

[1] Barlow, *On Magnetic Attraction* (1823), 279; and *Encyclopædia Metropolitana* (1824), iv. art. *Electromagnetism*, 36.

[2] *Silliman's Journal*, xx. 340, 1831. Also Henry, *Scientific Writings* (1886), i. 54.

[3] *Annali delle Scienze Lombardo-Veneto*, March 1834.

[4] *Phil. Trans.*, 1833 [2], 318.

[5] *L'Institut*, lxxxii. Dec. 1834.

[6] See *Annals of Electricity*, ii. 1838; *Encyclopædia Britannica* (ed. vii.) art. *Voltaic Electricity*, 687

[7] *Silliman's Journal*, xxxiii. 1838; and [2] x. 344 and 473, 1850.

[8] Specification of Patent, 9022 of 1841.

[9] See *Cosmos*, x. 495, 1857, and *La Lumière Électrique*, ix. 193, June 1883.

[10] *Nuovo Cimento*, xix. 378, 1865.

[11] See Sturgeon's *Annals of Electricity*, iii. 384, 1838; and *Pogg. Ann.*, xxxi. 483, 1838.

[12] *Mémoire sur la Théorie des Machines électromagnétiques.*

[13] Specification of Patent, 2587 of 1860.

[14] Specification of Patent, 2830 of 1882. See *Journ. Soc. Telegr. Engineers*, xii. 301, 1883.

1882 Ayrton and Perry made the important discovery of the automatic regulation of motors, to run with constant velocity, by methods akin to, but the converse of, those adapted for making dynamos self-regulating. Since that date, the improvements made in continuous current motors, though great, have been in mechanical perfection of design and detail. The alternate-current dynamo does not make a convenient alternate-current motor, as it is not self-starting. When once started, however, it runs in absolute synchronism with the generator. Bailey, in 1879, showed how to produce rotation by the currents induced in a copper disk placed in a systematically shifting magnetic field. Ferraris, in 1888, made the important suggestion to drive a motor by two independent alternate currents of similar period, but differing in phase, thus producing a rotating magnetic field. The same suggestion came independently from Nikola Tesla, who first put such motors into practical form. Many forms of rotatory-field motors have since been devised; various engineers, including Dolivo-Dobrowolsky, C. E. L. Brown and others, have brought the induction motor to a remarkable pitch of perfection. In the States a two-phase motor on a different plan has been perfected by Stanley and Kelly. The success of these polyphase motors, in which the rotating part is an entirely independent simple structure of iron and copper, receiving its currents by induction and without any commutator or circuit connexions, has led to the device of single-phase motors for use with simple alternate currents. The structure of these motors resembles that of the polyphase motors, since the revolving part receives its currents solely by induction.

The theory of the dynamo dates back to the investigations of Weber[1] and of Neumann[2] respecting the general laws of magneto-electric induction, followed by Jacobi's[3] calculations and experiments respecting the performance of an electric motor, by Poggendorff's[4] and Koosen's[5] investigations of the theory of the Saxton magneto machine, and by the researches of Lenz,[6] Joule,[7] Le Roux,[8] and of Sinsteden[9]

[1] *Elektrodynamische Maasbestimmungen* (1846).

[2] *Berliner Berichte*, p. 1, 1845; and p. 1, 1847.

[3] *Pogg. Ann.*, li. 370, 1840; lxix. 181, 1846; and *Krönig's Journal*, iii. 377, 1851. Also *Ann. Chim. Phys.* [3] xxxiv. 451, 1852.

[4] *Pogg. Ann.*, xlv. 390, 1838.

[5] *Pogg. Ann.*, lxxxv. 226; and lxxxvii. 386, 1852.

[6] *Pogg. Ann.*, xxxi. 483, 1834; xxxiv. 385, 1835; and xcii. 128, 1854.

[7] *Annals of Electricity*, iv. v. 1839–40; *Phil. Mag.* [3] xxiii. 263, 347 and 435, 1843.

[8] *Ann. Chim. Phys.* [3] l. 463, 1857.

[9] *Pogg. Ann.*, lxxxiv. 181, 1851.

These researches were followed at a long interval by those of Favre,[1] followed by silence for twenty years, broken only by the pregnant, but almost totally forgotten, little paper in which Clerk-Maxwell[2] laid down a theory for self-exciting machines. On the revival of electric lighting the theory of the dynamo was again studied, important contributions being made by Mascart,[3] Hagenbach,[4] von Waltenhofen,[5] Hopkinson,[6] Herwig,[7] Meyer[8] and Auerbach,[9] and Joubert. The latter founded the modern theory of alternate-current machines. Hopkinson[10] devised the method of representing, by a curve, the relation between the current and the working electromotive-force of the machine; such curves, under the name of "characteristics," subsequently formed the basis of the theoretical researches of Marcel Deprez.[11] In 1880 Frölich[12] began a series of investigations, both experimental and theoretical, that led to equations of remarkable simplicity, if not of more than approximate value, and in 1883 Clausius,[13] adopting Frölich's fundamental expression for the law of the electromagnet, evolved with great elaboration a theory in which all the various secondary effects arising in generators were taken into account—a theory which he later extended to the case of motors. In 1886 John and Edward Hopkinson[14] published a remarkable paper, developing, from theoretical considerations respecting the induction of magnetism in a magnetic circuit of given form and materials, a theory of the dynamo, the perfection of which may be judged by the fact that its use, as now extended by various workers, enables the performance of a machine to be predicted with extraordinary accuracy from the design as laid down in the working drawings. Other contributions to the theory of dynamos have been made by Lord Kelvin[15] (windings to secure maximum efficiency),

[1] *Comptes Rendus*, xxxiv. 342, 1853; xxxix. 1212, 1854; xlvi. 337, 658, 1858.
[2] *Proc. Royal Soc.*, Mar. 14, 1867; and *Phil. Mag.* [4] xxxiii. [474], 1867.
[3] *Journal de Physique*, vi. 204, 297, 1877; and vii. 89, 1878.
[4] *Archives des Sciences Physiques*, lv. 255, March 1876; and *Pogg. Ann.*, clviii. 599, 1876.
[5] *Wiener Berichte*, lxxx. 601, 1879.
[6] *Proc. Inst. Mech. Engineers*, 238, 1879, and 266, 1880.
[7] *Wied. Ann.*, viii. 494, 1880.
[8] *Wied. Ann.*, viii. 494, 1879.
[9] *Ann. de l'École Normale*, x. 131, 1881; and *Journal de Physique* [2] ii. 293, 1883.
[10] *Proc. Inst. Mech. Engineers*, 238, 1879.
[11] *Comptes Rendus*, xcii. 1152, 1881; and *La Lumière Électrique*, xv. 1, 1885.
[12] *Berl. Berichte*, 962, 1880; *Electrotechnische Zeitschrift*, ii. 134, 170, 1881; vi. 128, etc., 1885; and ix., Nov. 1888.
[13] *Wied. Ann.*, xx. 353, 1883; xxi. 385, 1884; *Phil. Mag.* [5] xvii. 49 and 119, 1884.
[14] *Phil. Trans.*, i. 331, 1886.
[15] *Journal de Physique* (2) ii. 240, 1887; and *Comptes Rendus*, xciii. 474, 1881.

Kapp[1] (pre-determination of characteristic curve), Rücker[2] (limits of self-regulation), Esson[3] (design of multipolar machines), and others. Hering,[4] Fritsche,[5] and Arnold[6] have published studies on the modes of winding armatures; and the latter has given a formula for all kinds of continuous-current machines with closed-coil armatures. Methods of analysing the various losses of energy due to friction, hysteresis and eddy-currents have been devised by Mordey,[7] and later by Kapp[8] and Housman,[9] independently. The theory of alternate current motors both of the asynchronous and of the synchronous types has of late received much attention from various writers.[10]

[1] *Journ. Soc. Telegr. Engineers*, xv. 518, 1887.

[2] *Phil. Mag.* (5) xix., 462, June 1885.

[3] *Journal Inst. Electrical Engineers*, xx. 1891.

[4] Hering's *Principles of Dynamo-electric Machines*, New York, 1889.

[5] Fritsche's *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

[6] Arnold's *Die Ankerwickelung der Gleichstrom-Dynamomaschinen*, Berlin, 1891.

[7] *Journal Inst. Electrical Engineers*, xviii. 620, 1889.

[8] *Electrician*, xxvi. 700, 1891.

[9] *Ib.*; see also *Journal Inst. Electrical Engineers*, xx. 303, 1891.

[10] Ferraris, "Rotazioni elettrodynamiche," *Turin Acad.*, March 1888.

L. Duncan, "Alternate Current Motors," *Elec. World* (N.Y.), xvii. 341, 357.

Hutin and Leblanc, *La Lumière Electrique*, xl. 373.

Dr. J. Sahulka, *Ueber Wechselstrom-Motoren*, Leipzig, 1892.

R. V. Picou, *Les Moteurs Électriques à champ magnétique tournant*, Paris, 1892.

E. Arnold, *Theorie und Berechnung der asynchronen Wechselstrom-Motoren*; and see articles by same author in *Elec. World* (N.Y.), 1893-4.

G. Ferraris, "A Method for the Treatment of Rotating or Alternating Vectors, &c.," *Electrician*, 1894, xxxiii. 110, 129, 152, 184.

Reber, "Two- and Three-phase Motors," *Amer. Inst. Elec. Eng*, October 1894.

Steinmetz, *Amer. Inst. Elec. Engineers*, December 1894, p. 803.

A. Potier, "Sur les Moteurs à induit fermé sur lui-même," *Bull. de la Soc. Internationale des Électriciens*, May 1894, 248.

De Bast, *Bull. de l'Assoc. des Ingénieurs Électriciens*, Aug. 1893.

G. Ferraris, "A Method for the Treatment of Rotating or Alternating Vectors, &c.," *The Electrician*, xxxiii. 110, 129, 152, 184.

Dr. J. Hopkinson, "On the Theory of Alternating Currents, particularly in reference to Two Alternate-Current Machines connected to the same Circuit," *Journ. Soc. Teleg. Engineers*, xiii. 496, 1884.

W. M. Mordey, "On Parallel Working, with special reference to Long Lines," *Inst. of Elec. Engineers*, xiii. 260, 1894.

Blondel, "Couplage des Alternateurs," *La Lumière Elec.*, xlv. 351, 1892.

Steinmetz, "Theory of a Synchronous Motor," *Amer. Inst. Elec. Engineers*, Oct. 17, 1894.

Picou, "Transmission de Force par Moteurs Alternatifs Synchrones," *Soc. Internationale des Electriciens*, Feb. 1895.

Bedell and Ryan, "Action of a Single-Phase Synchronous Motor," *Journ. Franklin Inst.*, March 1895.

Rhodes, "Theory of the Synchronous Motor," *Proc. Physical Society*, 1895.

CHAPTER III.

PHYSICAL THEORY OF DYNAMO-ELECTRIC MACHINES.

ALL dynamos are based upon the discovery made by Faraday in 1831, that electric currents are generated in conductors by moving them in a magnetic field. Faraday's principle may be enunciated as follows:—When a conductor is moved in a magnetic field so as to cut the lines of force, there is an electromotive-force induced in the conductor, in a direction at right angles to the direction of the motion, and at right angles also to the direction of the lines of force.

Dr. Fleming has given a most useful rule for remembering this connexion between motion, magnetism, and induced electromotive-force. Hold the thumb and the first and middle fingers of the right hand as nearly as possible at right angles to each other, as in Fig. 9, so as to represent three rectangular axes in space. If the thumb point in the direction of the motion, and the forefinger point along the direction of the magnetic lines, then the middle finger will point in the direction of the induced electromotive-force.[1]

This induced electromotive-force is, as Faraday showed, proportional to the number[2] of magnetic lines cut per second; and is, therefore, proportional to the density of the magnetic field, and to the length and velocity[3] of the moving conductor.

[1] A more usual rule for remembering the direction of the induced currents is the following adaptation from Ampère's well known rule:—Supposing a figure swimming in any conductor to turn so as to look along the (positive direction of the) lines of force. Then if he and the conductor be moved towards his right hand, he will be swimming with the current induced by this motion.

[2] For the numerical signification to be attached to the term "number of magnetic lines," see p. 113.

[3] If the direction of the motion is not at right angles to the direction of the field, the resolved part of the velocity in the direction at right angles to the field must be considered as the effective velocity.

For steady currents, the flow of electricity in the conductor is, by Ohm's well-known law, directly proportional to this electromotive force, and inversely proportional to the resistance of the conductor. For sudden currents, or currents whose strength is varying rapidly, this is no longer true. And it is one of the most important matters, though one too often overlooked in the construction of dynamo-electric machinery, that the "resistance" of a coil of wire, or of a circuit, is by no means the only obstacle offered to the generation of a momentary current in that coil or circuit; but that, on the contrary, the "self-induction" exercised by one part of a coil or circuit upon another part or parts of the same, is a consideration, in many cases quite as important as, and in some cases more important than, the resistance.

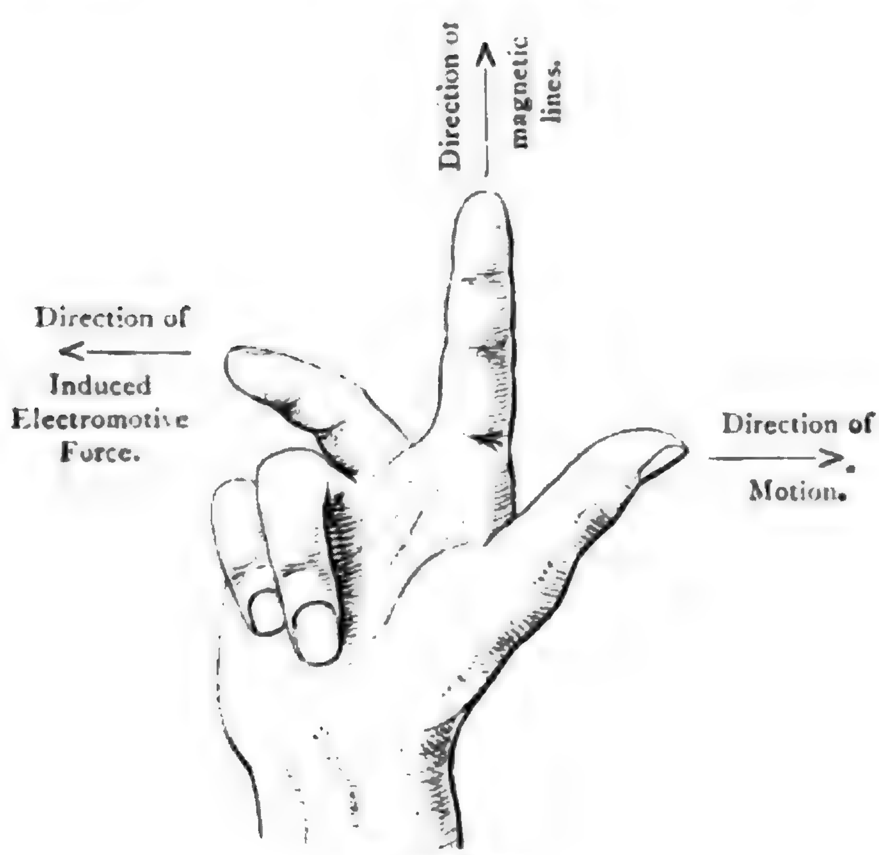


FIG. 9.—ILLUSTRATION OF FLEMING'S RULE.

To understand clearly Faraday's principle—that is to say, how it is that the act of moving a wire so as to cut magnetic lines of force can induce or generate a current of electricity in that wire—let us inquire what a current of electricity is.

A wire through which a current of electricity is flowing looks in no way different from any other wire. No man has ever yet seen the electricity running along in a wire, or knows precisely what is happening there. Indeed, it is still a disputed point which way the electricity flows, or whether or not there are two currents flowing simultaneously in opposite directions. One thing is certain ; that the energy does not flow along the substance of the wire at all, but is transmitted across the surrounding medium, transversely. Until we know

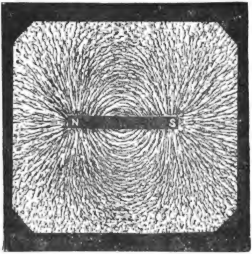


FIG. 10.—MAGNETIC FIELD OF BAR-MAGNET.

with absolute certainty what electricity is, we cannot expect to know precisely what a current of electricity is. But no electrician is in any doubt as to one most vital matter, namely, that when that which is called an electric current flows through a wire, the magnetic forces with which that wire is thereby, for the time, endowed, reside not in the wire at all, but in the space surrounding it. Every one knows that in the space or " field " surrounding a magnet there are magnetic forces whose direction and intensity are conveniently portrayed by magnetic " lines of force." These lines start in

tufts from the N-pointing pole and curve round to the S-pointing pole of the magnet. They are invisible until, by dusting iron filings into the field, their presence is made known, though they are always in reality there (Fig. 10), and can be detected in several independent ways. A view of the magnetic field at the pole of a bar magnet, as seen end-on, would, of course, exhibit merely radial lines, as seen in Fig. 11.

Now, every electric current (so called) is surrounded by a magnetic field, the lines of which can be similarly revealed.

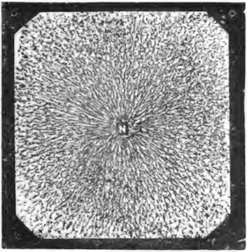


FIG. 11.—MAGNETIC FIELD ROUND ONE POLE, END-ON.

To observe them, a hole is bored through a card or a piece of glass, and the wire which carries the current must be passed up through the hole. When iron filings are dusted into the field they assume the form of concentric circles (Fig. 12), showing that the lines of force run completely round the wire, and do not stand out in tufts. In fact, every conducting wire is surrounded by a sort of magnetic whirl, like that shown in Fig. 13. A great part of the energy of the so-called electric current in the wire consists in these external magnetic whirls. To set them up requires an expenditure of energy ; the current

on being started does not instantly assume its full strength, part of its energy is being employed during the variable period in building up this surrounding field. On stopping the current by breaking the circuit this surrounding energy returns back into the circuit, the field, as it collapses upon the wire, tending to maintain the current, and causes the spark seen at the break of the circuit. It is these magnetic whirls which act on

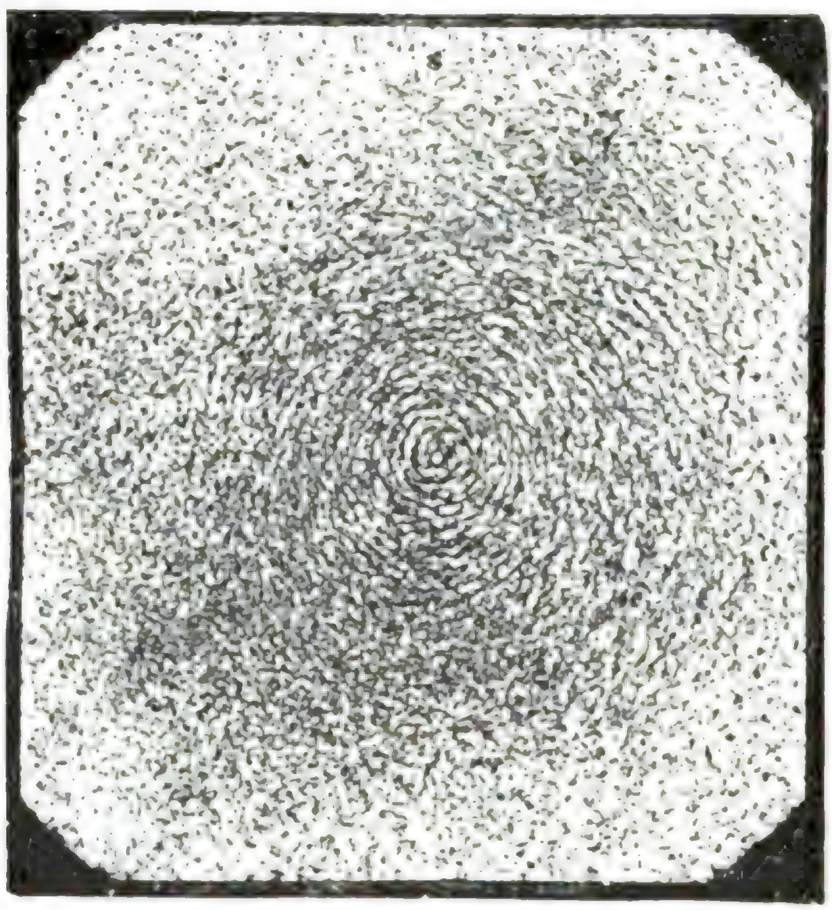


FIG. 12.—MAGNETIC FIELD SURROUNDING CURRENT. THE CONDUCTING WIRE SEEN END-ON.

magnets, and cause them to set, as galvanometer needles do, at right angles to the conducting wire.

Now, Faraday's principle of induction is nothing more or less than this:—That by moving a wire near a magnet, across a space in which there are magnetic lines, the motion of the wire, as it cuts across those magnetic lines, sets up magnetic whirls round the moving wire, or, in other language, generates a so-called current of electricity in that wire. Poking a magnet pole into a loop or circuit of wire also necessarily generates a momentary current in the wire loop, because it

momentarily sets up magnetic whirls. In Faraday's language, this action increases the number of magnetic lines embraced by the circuit.

It is, however, necessary that the moving conductor should, in its motion, so cut the magnetic field as to alter the number of magnetic lines that pass through the circuit of which the moving conductor forms part. Without a variation in the magnetic flux that penetrates the circuit there will be no induction. And induction will always occur in any circuit when any change in the flux takes place, however that change may be produced. If a conducting circuit—a wire ring or single coil, for example — be moved along in a uniform magnetic field, as indicated in Fig. 14, so that only the same lines of force pass through it, no current will be generated. Or if, again, as in Fig. 15, the coil be moved by a motion of translation to another part of the uniform field, as many lines of force will be left behind as are gained in advancing from its first to its second position, and there will be no current generated in the coil: the flux of magnetic lines has not varied. If the coil be merely rotated on itself round a central

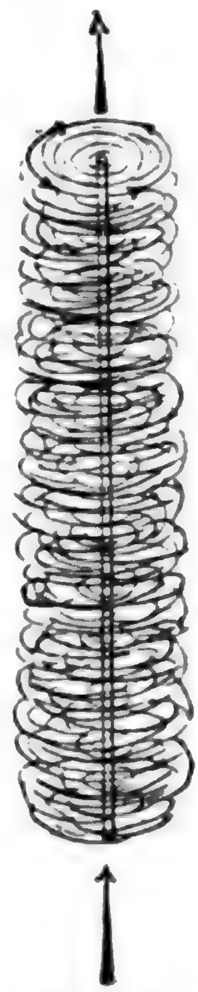


FIG. 13.
MAGNETIC WHIRL SURROUNDING WIRE CARRYING CURRENT.

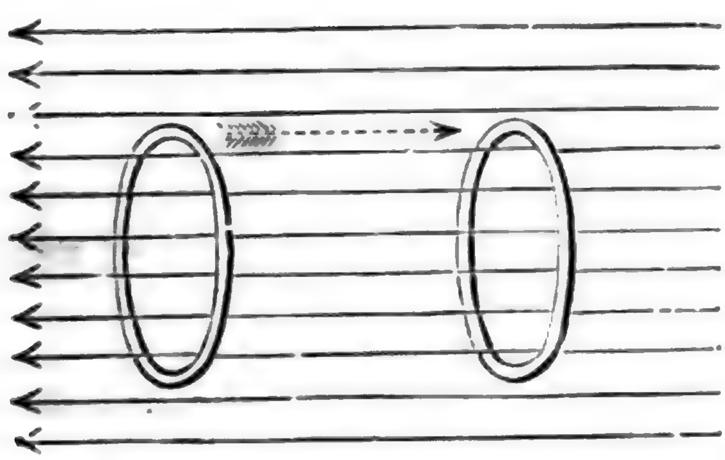


FIG. 14.—CIRCUIT MOVED WITHOUT CUTTING LINES OF FORCE OF A UNIFORM MAGNETIC FIELD.

axis, like the rim of a fly-wheel, it will not cut any more lines of force than before, and this motion will generate no current. But if, as in Fig. 16, the coil be tilted in its motion across the uniform field, or rotated round any axis in its own plane, then

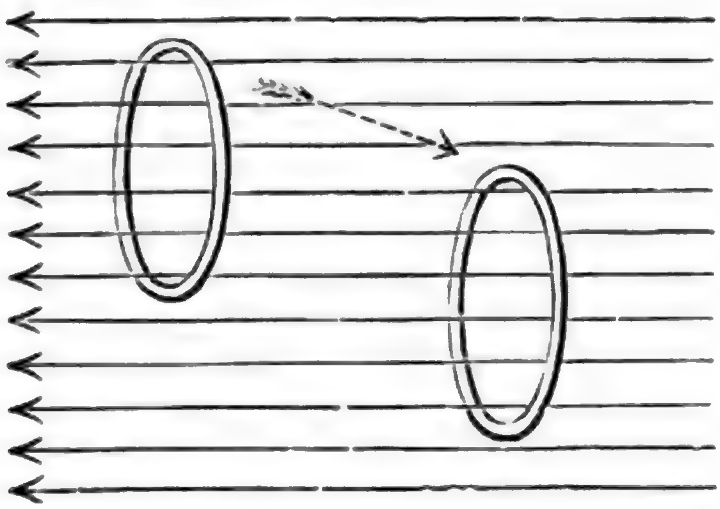


FIG. 15.—CIRCUIT MOVED WITHOUT CUTTING ANY MORE LINES OF FORCE.

the number of magnetic lines that traverse it will be altered and currents will be generated. These currents will flow round the ring coil in the right-handed direction (as viewed

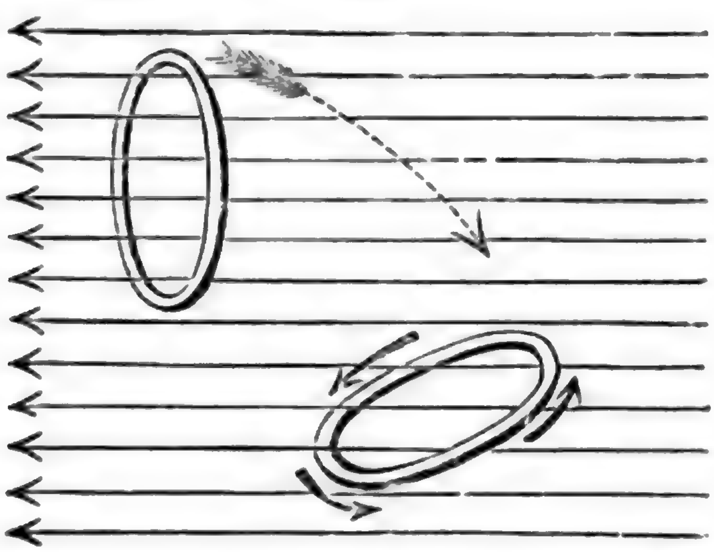


FIG. 16.—CIRCUIT MOVED SO AS TO ALTER NUMBER OF LINES OF FORCE THROUGH IT.

by a person looking along the magnetic field in the direction in which the magnetic lines run), if the effect of the movement is to diminish the number of lines of force that cross the coil; they will flow round in the opposite sense if the effect of the

movement is to increase the number of intercepted lines of force.

If the magnetic field be not a uniform one, then the effect of taking the coil by a simple motion of translation from a place where the lines of force are dense to a place where they are less dense, as from position 1 to position 2 in Fig. 17, will be to generate currents. Or, if the motion be to a place where the lines of force run in the reverse direction,[1] the effect will be the same, but even more powerful.

In the process called *homopolar* or "unipolar" induction (Chap. XIX.), conductors with sliding contacts move continuously through a uniform field; there being no reversals.

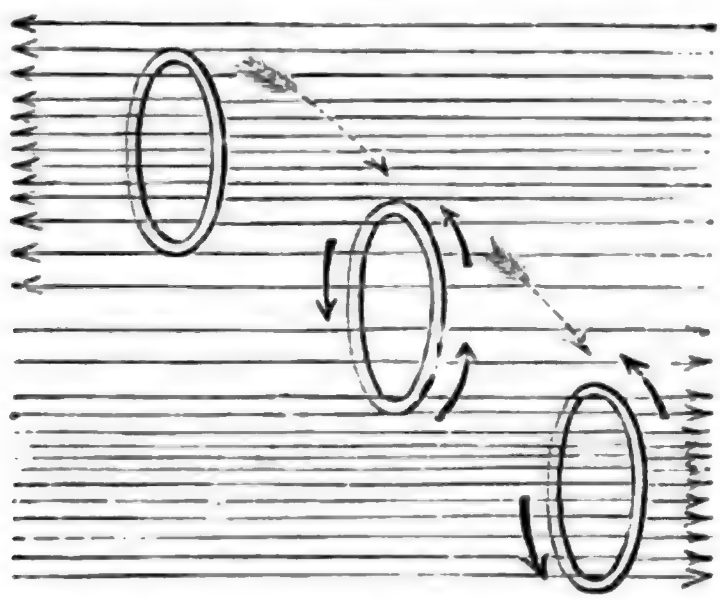


FIG. 17.—MOTION OF CIRCUIT IN NON-UNIFORM MAGNETIC FIELD.

We may now summarise the points under consideration and some of their immediate consequences, in the following manner:—

(1) To induce currents in a conductor there must be relative motion between conductor and magnet, of such a kind as to alter the number of magnetic lines embraced in or enclosed by the circuit.

(2) Increase in the number of magnetic lines embraced by the circuit generates an electromotive-force in the opposite sense to that induced by a decrease.

[1] As a matter of fact, it would be impossible to have a magnetic field exactly like Fig. 17; for in the intermediate part, between the upper and lower fields, the magnetic lines would be of curved complex form.

(3) The more powerful the magnet pole or magnetic field, the higher will be the electromotive-force generated.

(4) The more rapid the motion, the higher will be the electromotive-force.

(5) By joining in series a number of such moving conductors, the electromotive-forces in the separate parts are added together; hence very high electromotive-forces can be obtained by using numerous coils properly connected.

(6) Since the quantity or strength of the current depends on the resistance of the conductors in the circuit, as well as on the electromotive-force, all unnecessary resistance should be avoided.

(7) The number of magnetic lines being finite, the process of a generating machine in alternately increasing and diminishing the flux enclosed by the moving conductor must necessarily generate currents alternate in direction.

(8) By using a suitable commutator, all the currents, direct or inverse, induced during recession or approach, can be turned into the same direction in the wire that goes to supply currents to the external circuits; and if the rotating coils are properly grouped so that before the electromotive force in one set has died down another set is coming into action, then it will be possible, by using an appropriate commutator, to combine their separate currents into one practically uniform continuous current.

(9) As induction depends upon the relative motion of conductor and magnetic lines, it is a mere question of mechanical convenience whether the magnet be stationary while the copper conductor moves, or whether the conductor is fixed while the magnet moves.

(10) To the conductor which is generating the electromotive-force by cutting the magnetic lines, it makes no difference what the origin of those lines is, whether from a permanent magnet of steel or from an electromagnet, provided the number of magnetic lines so cut is the same.

(11) To the moving conductor it makes no difference what the origin of the motion is. Whether the motion be due

to a steam-engine, or to a gas-engine, or to hand-driving, or to driving by means of an electric current in the wire itself (as in the case of electric motors), it makes no difference to the moving conductor, which, provided the speed and the number of magnetic lines to be cut are given, will generate the same electromotive-force.

To make more clear the considerations which will occupy us when discussing individual types of dynamo, we will first examine some fundamental points in the general mechanism and design of dynamo machines. We will deal with the various matters in order, beginning with the various organs or parts of the machine. Having discussed these, we take up the nature of the processes that go on in the machine when it is at work, the action of the magnetic field on the rotating armature, the reactions of the armature upon the field in which it rotates. We must then enter upon the magnetic part of the subject, and discuss the magnetic properties of iron so far as is needed for the purpose of dynamo design. We shall then consider the design of field-magnets, and the design and construction of armatures.

Organs of Dynamo-Electric Machines.

The simplest conceivable dynamo is that sketched in Fig. 18, consisting of a single rectangular loop of wire rotating in a simple and uniform magnetic field between the poles of a large magnet. If the loop be placed at first in the vertical plane, the number of lines that pass through it from right to left will be a maximum, and as it is turned into the horizontal position the number diminishes to zero; but on continuing the rotation the lines begin again to penetrate the loop from the opposite side, so that there is a negative maximum when the loop has been turned through 180°. During the half-revolution, therefore, currents will have been induced in the loop, and these currents will be in the direction from back to front in the part of the loop which is rising on the left, and in the opposite direction, namely, from front to back, in that

part which is descending on the right. On passing the 180° position, there will begin an induction in the first sense, for now the number of negative lines of force is diminishing, which is equivalent to a positive increase in the number of lines of force: and this increase would go on until the loop reached its original position, having made one complete turn. If, then, to each end of the loop there were separately attached a metal collar on the shaft, and on each collar there pressed a spring, wires connected to these springs would convey an *alternating current* to the circuit. If, however, it is desired to adapt the apparatus to furnish a continuous current, a special adjunct must be added.

To commute these alternately-directed currents into one direction in the external circuit, there must be applied a *commutator* consisting of a metal tube slit into two parts, and mounted on a cylinder of hard wood or other suitable insulating material; each half being connected to one end of the loop, as indicated in Fig. 18. Against this commutator press a couple of metallic springs or "brushes" (Fig. 19), which lead away the currents to the main circuit. It is obvious that if the brushes are so set that the one part of the split tube slides out of contact, and the other part slides into contact with the brush, at the moment when the loop passes through the positions when the induction reverses itself, the alternate currents induced in the loop will be "commuted" into one direction through the circuit. We should expect, therefore, the brushes to be set so that the commutation shall take place exactly as the loop passes through the vertical position. In practice, however, it is found that a slight forward lead must be given to the brushes, for reasons which will presently appear. In Fig. 20 are shown the brushes B B′, displaced so as to touch the

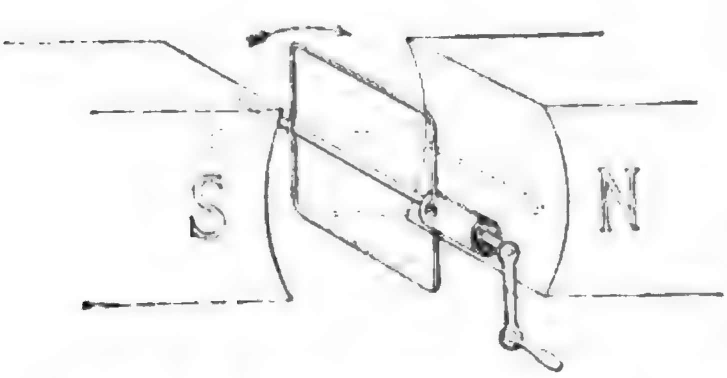


FIG. 18.—IDEAL SIMPLE DYNAMO.

commutator not exactly at the highest and lowest points, but at points displaced in the direction of the line D D, which is called the "diameter of commutation." The argument is in no wise changed if for the single ideal loop we substitute, as proposed by Sturgeon in 1835, the simple rectangular coil represented in Fig. 21, consisting of many

FIG. 19.—TWO-PART COMMUTATOR.

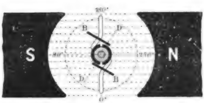


FIG. 20. SIMPLE LOOP IN SIMPLE FIELD.

turns of wire, in each of which a simultaneous inductive action is going on, making the total induced electromotive-force proportionately greater. This form, with the addition of an iron core, is, indeed, the form given to armatures in 1856 by Siemens, whose shuttle-wound armature is represented in section in Fig. 22. A small magneto-electric machine of the

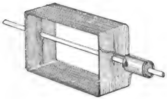


FIG. 21. SIMPLE RECTANGULAR COIL.

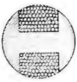


FIG. 22.—SECTION OF OLD SHUTTLE-WOUND SIEMENS ARMATURE.

old pattern, having the shuttle-wound armature, is shown in Fig. 23. Though this form has now for many years been abandoned, save for small motors and similar work, it gave a great impetus to the machines of its day; but for all large work it has been entirely superseded by the ring armatures and drum armatures presently to be described.

We have seen that the dynamo in its simplest form consists of two main portions: (1) an *armature*, which in revolving induces electromotive forces in the copper conductor wound upon it; (2) a *field-magnet*, that is to say a magnet whose function is to provide a field of magnetic lines, to be cut by the armature conductors as they revolve. In all dynamos, whether for continuous currents or for alternate currents, these two parts can be recognised. In almost all continuous-current machines the field-magnet stands still, and consists of

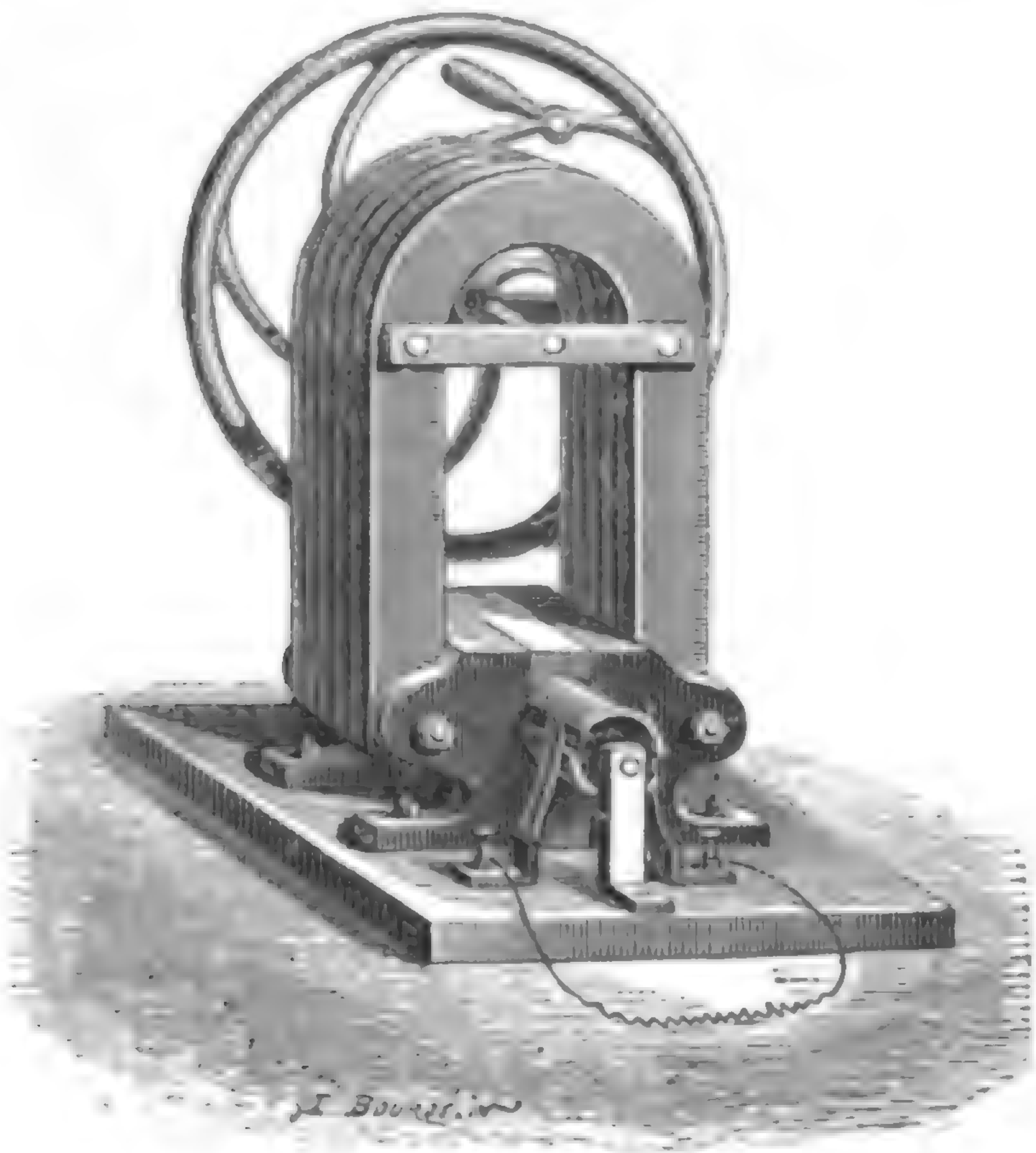


FIG. 23.—OLD SIEMENS MACHINE, WITH SHUTTLE-WOUND ARMATURE AND PERMANENT MAGNETS.

a comparatively simple and massive electromagnet; whilst the armature, which is a more complex structure, is the portion which rotates. In alternate-current machines the field-magnet is usually multipolar, and in the majority of cases is stationary, whilst the armature rotates; nevertheless there are many alternators of recent pattern in which the armature stands still and the field-magnet rotates. The criterion as to which portion is properly called "field magnet," and which "armature," is not the question of rota-

tion or otherwise. The name of field-magnet is properly given to that part which, whether stationary or revolving, maintains its magnetism steady during the revolution; and the name armature is properly given to that part which, whether revolving or fixed, has its magnetism changed in a regularly repeated fashion when the machine is in motion. In a generator the armature is that part which is connected in circuit with the distributing mains and gives current to them. In a motor the armature is that part which receives the currents from the mains. In the case of continuous-current machines there is another feature of first importance, namely, the apparatus for collecting the currents from the revolving armature. This apparatus consists of two essential parts: the *commutator* (or *collector*) attached to the armature and revolving with it, and the *brushes*. The latter, which are conducting contact pieces held pressed against the surface of the rotating commutator, are provided with special *brush-holders* mounted upon an adjustable frame or *rocker*.

In the case of alternate-current machines there is no need of a commutator; but, in general, these machines have to be provided with some device for making a sliding connexion. For in those forms in which the armature rotates, its coils must be brought into continuous metallic relation with the conductors of the main circuit; and in those forms in which the armature is stationary and no such arrangement is needed at that part, there must still be sliding contacts to maintain the coils of the revolving field-magnet part in continuous metallic connexion with the auxiliary exciting circuit. In either case the appropriate device consists of a pair of *slip-rings*, against each of which a *brush* presses.

In addition to the electrical and magnetic features enumerated above, there are certain purely mechanical features which need to be considered. The revolving part must be mounted on an appropriate *spindle* or *shaft*, the design of which is a matter of mechanical engineering. To transmit the power from the spindle to the revolving conductors of the armature there are required *driving attachments* properly secured to the spindle. The spindle itself must be supported

D 2

in suitable *bearings*, and be provided with *lubricators* to secure cool running. To receive the power from the engine a *pulley* must be provided, unless the dynamo is to be driven direct by a *coupling* from an engine mounted on the same bed-plate. Lastly, the whole dynamo must be erected upon an appropriate *bed-plate*, which in some cases is placed upon *rails*, so that it may be shifted from time to time by the aid of tightening screws, as the belt grows slack.

In the considerations which follow, attention will be concentrated upon dynamos for generating continuous currents, the various organs of which will be duly considered. The design of alternate-current machines will be discussed in a later chapter.

ARMATURES.

Returning to the ideal simple loop, we may exhibit it in its relation to the 2-part commutator somewhat more clearly by referring to Fig. 24. The same split-tube or 2-part commutator will suffice if a loop of two or more turns be substituted, as shown in Fig. 25, for the single turn.

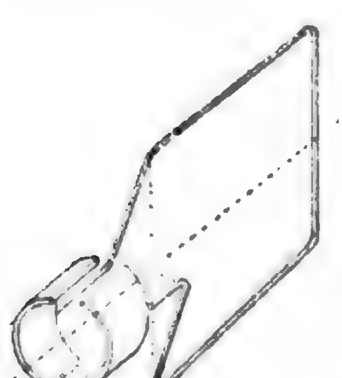


FIG. 24.—SIMPLE LOOP ARMATURE.

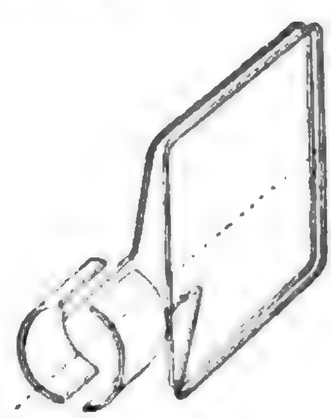


FIG. 25.—LOOP ARMATURE OF TWO TURNS.

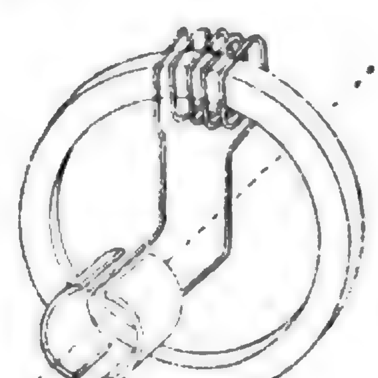


FIG. 26.—SIMPLE RING ARMATURE WITH ONE COIL.

But we may substitute also for the one loop a small coil consisting of several turns wound upon an iron ring. This coil (Fig. 26), which may be considered as one section of a Pacinotti or Gramme ring, will be penetrated by magnetic lines as the loop was. In the position drawn, it occupies the highest point of its path, and the flux of magnetic lines

through it will be a maximum. As it turns, the number of lines that penetrate it will diminish, and become zero when it is at 90° from its original position. But a little consideration of its action will suffice to show that if another coil be placed at the opposite side of the ring it will be performing an exactly similar inductive action at the same moment, and may therefore be connected to the same commutator. If these two coils are united in parallel, as shown in Fig. 27, the joint electromotive force will be the same as that due to either separately; but the resistance offered to the current by the two jointly is half that of either. It is evident that we may connect two parallel loops in a similar fashion to one simple 2-part collector. If the two loops are of one turn each, we shall have

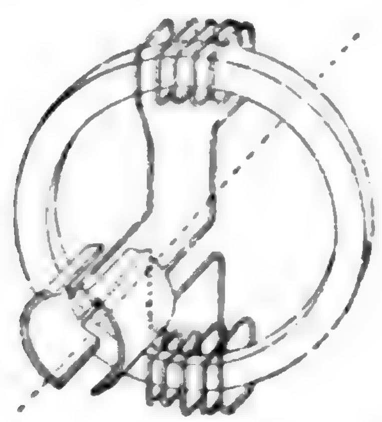


FIG. 27.—SIMPLE RING ARMATURE WITH TWO COILS IN PARALLEL.

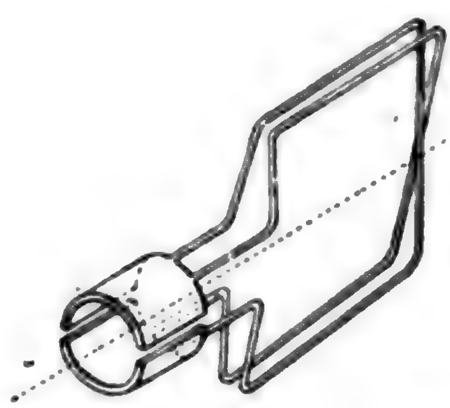


FIG. 28.—SIMPLE LOOP ARMATURE WITH TWO COILS IN PARALLEL.

the arrangement sketched in Fig. 28; but the method of connecting is equally good for loops consisting of many turns each.

Now, with all these arrangements involving the use of a 2-part commutator, whether there be one circuit only or two circuits in parallel in the coils attached thereto, there is the disadvantage that the currents, though commutated into one direction, are not absolutely continuous. In any single coil without a commutator there would be generated, in successive revolutions, currents whose variations may be graphically expressed by a recurring sinusoidal curve, such as Fig. 29. But if by the addition of a simple split-tube commutator the alternate halves of these currents are reversed, so as to rectify

their direction through the rest of the circuit, the resultant currents, though not continuous, will be of one sign only, as shown in Fig. 30, there being two currents generated during each revolution of the coil. The currents are now "rectified,"

FIG. 29.—SIMPLE CURVE OF SINES, REPRESENTING AN ALTERNATING OR UNDULATORY CURRENT.

or "redressed," as our continental neighbours say, but are not strictly continuous. To give *continuity* to the currents, we must advance from the simple 2-part commutator to a form having a larger number of parts, and employ therewith a

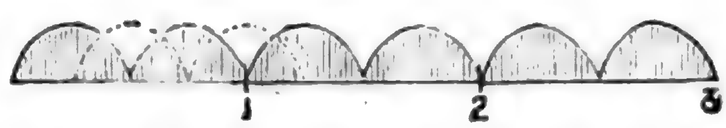


FIG. 30.—CURVE OF RECTIFIED OR COMMUTED ALTERNATING CURRENT.

larger number of coils. The coils must also be so arranged that one set comes into action while the other is going out of action. Accordingly, if we fix upon our iron ring two sets of coils at right angles to each other's planes, as in Fig. 31, so that one comes into the position of best action while the other is in the position of least action (one being parallel to the magnetic lines when the other is normal to them), and their actions be superposed, the result will be, as shown in Fig. 32, to give a current which is continuous, but not steady, having four slight undulations per revolution. If any larger number of separate coils are used, and their effects, occurring at regular intervals, be superposed, a similar curve will be obtained, but with summits proportionately more numerous and less elevated. When the number of coils used is very great, and the overlappings of the curves are still more complete, the row of summits will form practically a straight line,

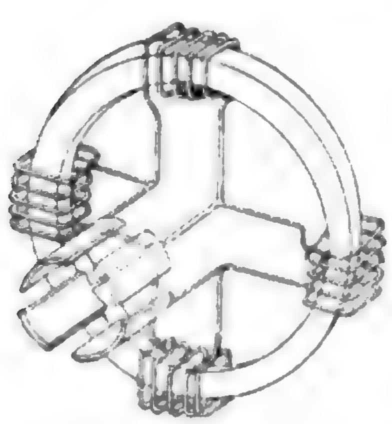


FIG. 31.—FOUR-PART RING ARMATURE (CLOSED COIL).

or the whole current will be practically constant. As arranged in Fig. 31, the four coils are all united together in a *closed* circuit, the end of the first being united to the beginning of the second, and so forth all round, the last section closing in to the first. In order to obtain greater uniformity of effect, the coils on the armature ought to be

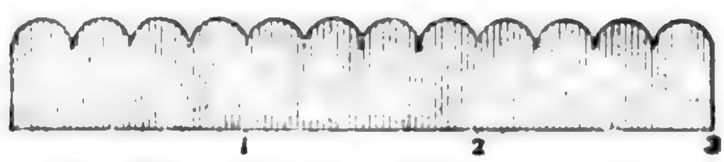


FIG. 32.—CURVE OF CONTINUOUS BUT NON-UNIFORM CURRENT.

divided into a very large number of sections (see Chap. IX.), which come in regular succession into the position of maximum effect at regular intervals one after the other. In Fig. 33 a sketch is given of a drum armature wound with two pairs of coils at right angles one to the other, and connected to a 4-part commutator. A little examination of Figs. 31 and 33 will show that each section of the coils is connected to the next in order to it; the whole of the windings constituting, therefore, a single closed coil. Also, the end of one section and the beginning of the next are both connected with a segment of the commutator. In practice, the commutator segments are not mere slices of metal tubing, but are built up of a number of parallel bars of copper, gun-metal, or phosphor-bronze, such as may be seen in Fig. 36, p. 42, placed round the periphery of a cylinder of some insulating substance. It will also be noticed that, owing to the fact that there is a continuous circuit all round, there are two ways in which the current may flow through the armature from one brush to the other, as in all the ring and drum armatures; of which, indeed, Figs. 31

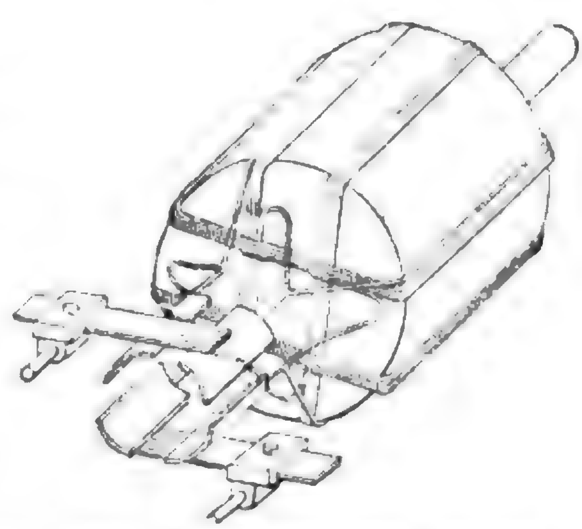


FIG. 33.—FOUR-PART DRUM ARMATURE (CLOSED COIL).

and 33 may be taken as simplified instances. The same reasoning now applied to 4-part armatures holds good for those having a still larger number of parts, such as is shown in Fig. 34 Of these more will be said in the subsequent chapters. Let it suffice to say here that in closed-coil armatures, whether of the "ring" or the "drum" type, there are usually as many segments to the commutator as there are *sections* or groups of coils in the circuit of the armature. The special case of *open-coil armatures* is considered in Chapter XVIII. In machines of this type the separate coils are not connected up together in series, and a special

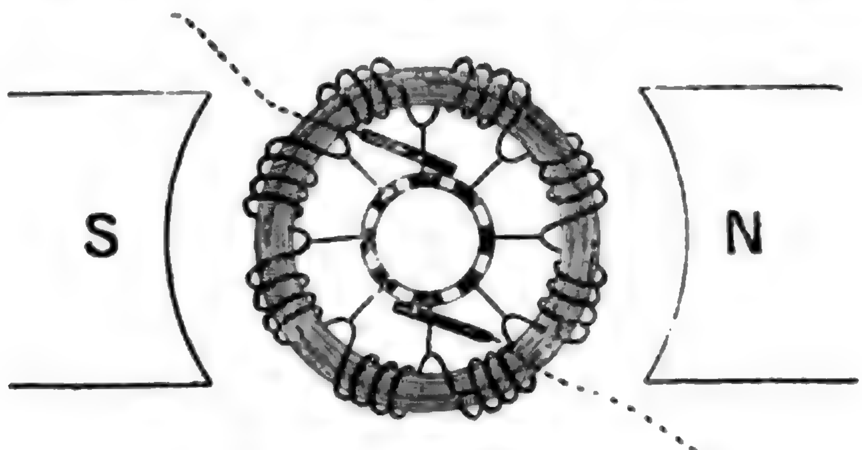


FIG. 34.—SIMPLE RING ARMATURE, SHOWING CONNEXIONS OF CLOSED COIL.

form of commutator is used instead of the usual arrangement of a large number of parallel bars.

So far, the only types of armature considered have been the "drum" type and the 'ring" type; but these are not the only possible cases. The object of all such combinations of coils is to obtain the practical continuity and equability of current explained above. To attain this end it is needful that some of the individual coils should be moving through the position of maximum action, whilst others are passing through the neutral point, and are temporarily idle. A symmetrical arrangement of the individual coils or groups of coils around an axis may take one of the four following types:—

(1) *Ring armatures*, in which the coils are grouped upon a ring whose principal axis of symmetry is its axis of rotation also.

(2) *Drum armatures*, in which the coils are wound longitudinally over the surface of a drum or cylinder.

(3) *Pole armatures*, having coils wound on separate poles projecting radially all round the periphery of a disk or central hub.

(4) *Disk armatures*, in which the coils are flattened into a disk.

The ingenuity of inventors has been exercised chiefly in three directions:—The securing of practical continuity, the avoidance of eddy currents in the cores, and the reduction of useless resistance. Most inventors have been content to secure approximate continuity by making the number of sections numerous. Pacinotti's early dynamo had the coils wound between projecting teeth upon an iron ring. Gramme preferred that the coils should be wound round the entire surface of the annular iron core. To prevent wasteful eddy currents in the core, he constructed it of varnished iron wire. For ring cores flat core-disks of sheet iron are now almost universally preferred. For discoidal ring armatures the core is built of hoops. In ring armatures the parts of the copper coils which pass through the interior of the ring are inoperative in cutting magnetic lines, unless there are pole-pieces of the field-magnet projecting internally. Hence, in the ordinary forms of dynamo with exterior magnets, the inner parts of the ring winding act merely as conductors and not as inductors, and offer a certain amount of wasteful resistance. But this resistance in well-designed machines is insignificant compared with that of the external circuit; and the disadvantage is largely imaginary. Inventors have essayed to reduce the amount of copper, by either fitting projecting flanges to the pole-pieces, or by using internal magnets, or else by flattening the ring into a disk form, so as to reduce the interior parts of the ring coils into an insignificant amount. Indeed, the flat-ring armatures may be said to present a distinct type from those in which the ring tends to the cylindrical form. In some large German dynamos of recent type the ring is outside the field-magnets, so that the outer part of the windings are non-inductive or idle; and the

currents are collected direct from the ring by brushes which trail on its periphery. The various modes of winding and connecting up the conductors on an armature are specially considered in Chapter XII. A finished ring armature with its commutator and driving pulley is shown in Fig. 35.

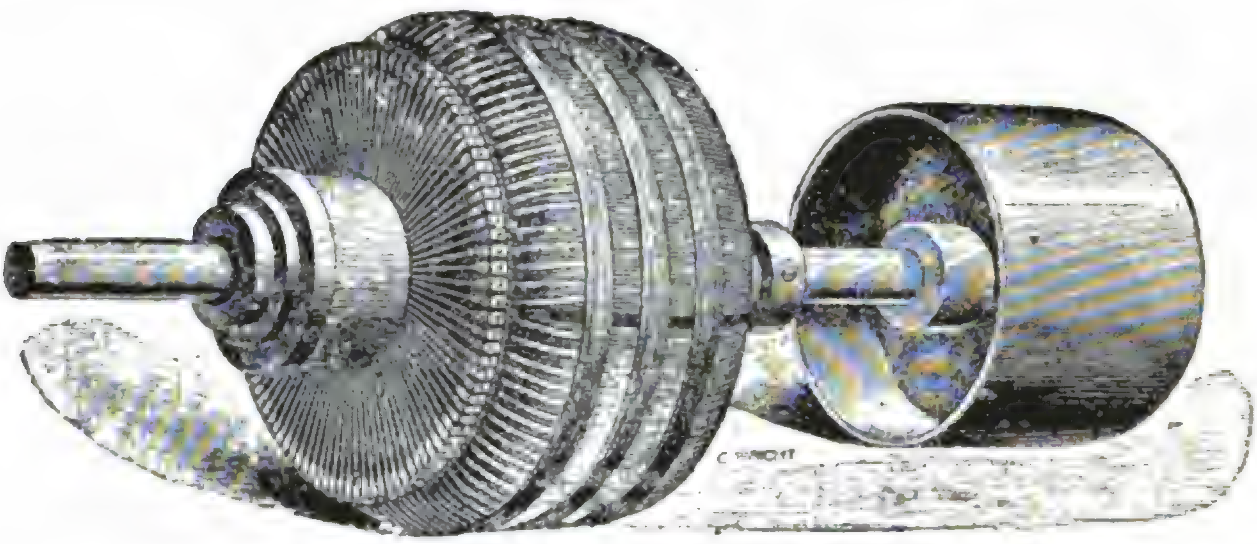


FIG. 35.—RING ARMATURE OF GRAMME DYNAMO (FULLER'S PATTERN).

Drum armatures, as first constructed by Siemens, had iron cores made of wire wound upon an internal non-magnetic nucleus. Weston substituted stamped core-disks of iron with teeth. Edison, iron core-disks without teeth. Special modes

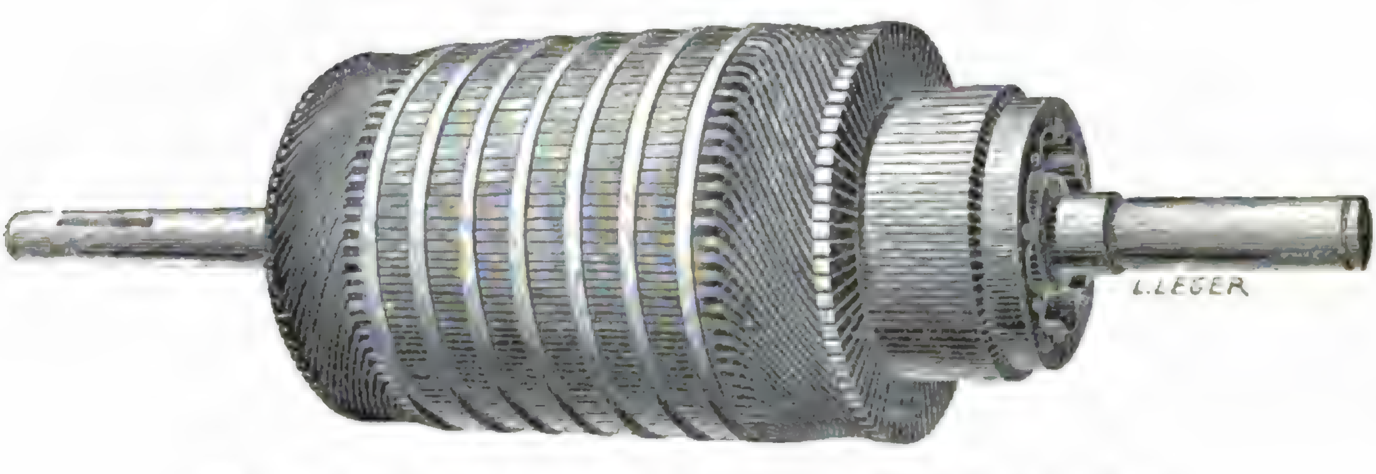


FIG. 36.—DRUM ARMATURE (ALLGEMEINE CO.'S PATTERN).

of winding or joining the copper conductors have been devised by many inventors. A complete drum armature is depicted in Fig. 36, which shows the overlapping of the windings at the end of the drum, the connexions to the commutator,

and the external binding wires that keep the coils from flying out.

Pole armatures, having the coils wound upon radially projecting poles, were devised by Allan, Lontin and Weston.

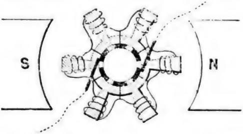


FIG. 37.—SIMPLE POLE ARMATURE SHOWING CONNEXIONS.

The principle of Lontin's machines, in which the coils are connected like the sections of a Pacinotti or Gramme ring, is indicated in Fig. 37. Here the diameter of commutation is parallel to the polar diameter, because the number of magnetic lines in this case is a maximum in the coils that are in the right and left positions. This is not a convenient construction of armature for continuous-current machines; for it does not admit of the winding being divided into a sufficiently numerous set of sections, and the self-induction in each section is too great.

FIG. 38.—DISK ARMATURE OF DESROZIERS' MACHINE.

Disk armatures are now differentiated into two kinds: (1) those in which the coils are grouped on a number of small bobbins, side by side, an arrangement suitable for

alternate-current machines, such as those of Siemens, Ferranti, and Mordey; (2) those in which the windings are made to overlap over a considerable angle of the periphery, as in the disk dynamos of Pacinotti, of Desroziers, and of Fritsche, all of which are adapted to give continuous currents. It is usual, in the disk form of armature, to dispense with any iron core; for the armature, being thin, can be inserted in a comparatively narrow gap between the polar surfaces of the field magnet. A disk armature is shown in Fig. 38, belonging to a Desroziers machine.

Armature Cores.

Whenever iron is employed in armatures, it must be slit or laminated, so as to prevent the generation of parasitic eddy-currents. Such iron cores should be structurally divided in planes normal to the circuits round which electromotive-force is induced; or should be divided in planes parallel to the magnetic flux and to the direction of the motion. Thus, drum armature cores should be built of disks of thin sheet iron. Ring armatures, if of the cylindrical or elongated type, should have cores made up of rings stamped out of sheet iron and clamped together side by side; but if of the flat ring type they should be built of concentric hoops. Cores built up of varnished iron wire, or of thin disks of sheet iron separated by varnish, asbestos paper, or mica, partially realize the required condition. The magnetic discontinuity of wire cores is, however, to a certain extent disadvantageous; it is better that the iron should be without discontinuity in the direction in which it is to be magnetized. It should, therefore, be laminated into sheets, rather than subdivided into wires. Cores of solid iron are quite inadmissible, as currents are generated in them and heat them. Cores of solid metal other than iron—for example, of gun-metal or of phosphor-bronze—should on no account be used in any armature.

FUNDAMENTAL POINTS IN DESIGN.

As has already been pointed out, the function of the field magnet is to provide a large number of magnetic lines, whilst the function of the armature is to cut the magnetic lines so provided. The iron core inside the armature may be regarded, therefore, as belonging to the magnetic circuit of the field magnet; the true armature consisting of the rotating copper conductors. There is no electrical necessity for the iron core inside the armature to rotate; indeed, in some ways it would act more efficiently if it did not. But purely mechanical considerations require that in both ring armatures and drum armatures the core should rotate with the coils. In all dynamos the electromotive-force is proportional at every instant to the rate at which the magnetic lines are being cut, and this will again be proportional to three quantities: (1) the number of magnetic lines provided by the field magnet; (2) the number of copper conductors connected together upon the armature; (3) the speed at which these conductors are driven. In alternate current dynamos the rate of cutting is continually changing in a regular periodicity; in continuous-current machines the rate of cutting is automatically averaged and made steady by the method of grouping the conductors around the ring or drum in a closed circuit, and connecting to the commutator. It is shown later, on p. 171, that, for continuous-current dynamos of the common two-pole type, the electromotive-force generated in the revolving armature may be calculated as follows:—

Let the speed of the armature, or revolutions *per second*, be called n.

Let the number of conductors that are joined in series with one another around the armature be called Z.

Let the number of magnetic lines which pass through the armature core from side to side be called N.

Let the number of volts of electromotive-force generated by the rotating armature be called E.

Then the following formula holds good :—

$$E = n \times Z \times N \div 100,000,000.$$

Example.—In a Kapp dynamo used at the Technical College, Finsbury, $Z = 120$; $N = 7,170,000$, at a speed of 780 revs. per min., or 13 revs. per sec., the whole electromotive-force generated is 111 volts.

For alternate-current machines the fundamental formula requires to be completed by the introduction of two additional factors. Such machines are usually multipolar, and if N represents the magnetic flux around any one of the individual magnetic circuits, the total magnetic effect must be increased by multiplying by the number p of pairs of magnetic poles that surround the armature. Further, a constant k must be inserted, the numerical value of which (varying from 1·1 to 2·5 in actual machines) depends on the relative breadths of the coils and pole-pieces employed. The general formula for the volts generated in any alternate-current machine will then be :—

$$E = k \times p \times n \times Z \times N \div 100,000,000.$$

Example.—In one of Kapp's alternators, $k = 2·3$; $p = 6$; $Z = 1190$; $N = 1,250,000$, when running at 700 revs. per min.; so that $n = 11·6$, $E = 2360$.

From the above formulæ it will be seen that the electromotive-force at which any dynamo is to deliver its current is the product of three factors; and it can be increased by increasing any one of the three, or all of them. In a given machine Z is a constant, and N, the magnetic flux, cannot be increased beyond the capacity of the iron core to carry magnetic lines. But if it is desired to design a new machine, obviously any value might be assigned to any of the three factors, provided the product came to the required amount. It is, therefore, a question of expediency whether in so designing a machine we will increase any one of the factors rather than any other. To increase N means using a larger cross section of iron, and a correspondingly big field-magnet, and therefore involves additional cost of iron. To increase Z means increasing the weight, and therefore the cost of the copper conductors; for the section of these depends on the

current they have to carry, whilst the electromotive-force generated depends on their number, and on the rate at which they cut the magnetic lines. Moreover, experience shows that thus increasing the quantity of copper upon an armature core of given size involves, when once a certain limit is reached, the very serious difficulty that the machine cannot be run without sparking at its brushes. To increase the speed n involves mechanical difficulties about lubrication and liability of the parts to fly out; in fact, mechanical considerations limit the speed. For many years modern practice has gone in the direction of keeping the speed slow, and in keeping down the relative amount of copper, the quantity of iron being relatively large; for not only so is the total cost of the machine less than it would be if the relative amounts of copper and iron were reversed, but the expense and trouble of maintenance is found to be less. Machines with a relatively massive and powerful field-magnet spark less, require less attention to regulation and need fewer renewals of the brushes and commutator than do those which have a comparatively weak field-magnet. Of late there has been some tendency, however, to a movement in the opposite direction, because if, by special designing, without sacrificing the advantages attained in the possession of a relatively powerful field-magnet, the speed and the weight of copper on the armature can be increased, the output of such a machine will be proportionally augmented at a small increase of total weight and total prime cost.

Methods of Exciting the Field Magnetism.

The five simple methods of exciting the magnetism that is to be utilised in the magnetic field may be grouped under two heads, according to whether the armature of the machine supplies the machine's own magnetism or whether the magnetism is provided for from some other source.

Magneto-dynamo.—In the oldest machines there was no attempt to make the machine excite its own magnetism, which

was provided for it once for all by the employment of a permanent magnet of steel. Unfortunately, the supposed permanent magnetism of steel magnets slowly decays, and is diminished by every mechanical shock or vibration to which the machine is subjected.

The *magneto-electric machine* or *magneto-dynamo*, a diagrammatic drawing of which is given in Fig. 39, survives, indeed, in numerous small types of machines. It has the serious disadvantage of being both heavier and bulkier than other dynamos of equal capacity, because steel cannot be permanently magnetised to the same high degree as that to which wrought iron or cast iron, or even steel itself, can be temporarily raised.

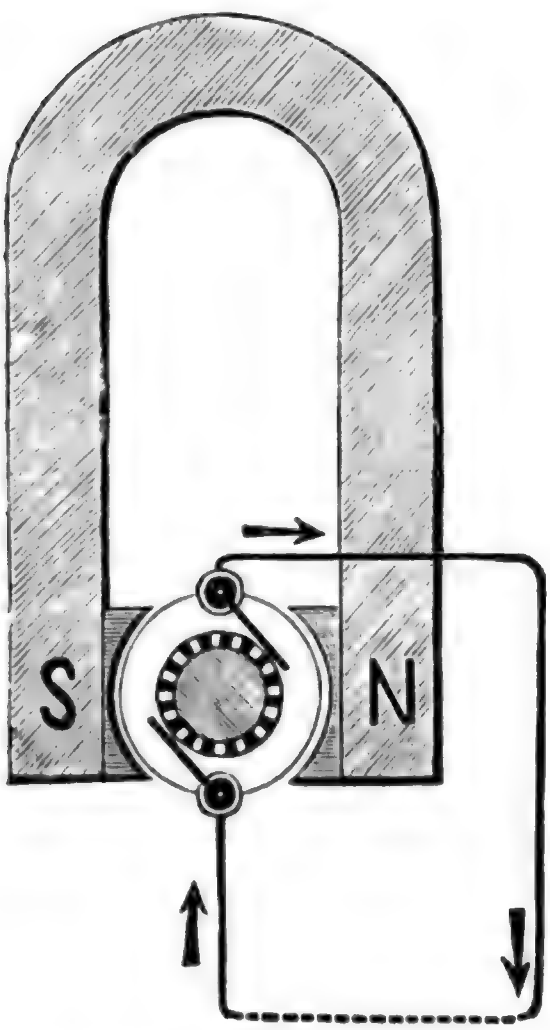


FIG. 39.—THE MAGNETO-DYNAMO.

Separately-excited Dynamo.—It was an obvious step to substitute for steel magnets, electro-magnets excited by means of currents from some independent source such as a voltaic battery. The *separately-excited dynamo* (Fig. 40) comes therefore second in the order of development. Though used by Faraday, this method did not come into acceptance until, in 1866, Wilde employed a small auxiliary magneto machine to furnish currents to excite the field magnets of a larger dynamo. The separately-excited dynamo, in common with the magneto machine, possesses the property that, saving for armature reactions, the magnetism in its field, and therefore the total electromotive-force of the machine, is independent of changes of resistance going on in the external circuit.

The dynamos of either of the preceding kinds can be

governed in three different ways: by altering the speed, by putting the brushes forward beyond the neutral point, or by altering the magnetic flux through the armature. For long it has been the fashion to control the electromotive-force of magneto machines by the device of providing a movable piece of iron, which could be placed more or less over the poles of the field-magnet, serving as a magnetic shunt to divert some of the magnetism from the armature. In the case of separately-excited machines there are two other methods of diminishing at will the effective magnetism, namely by weakening the exciting current, for example, by introducing less resistance into the exciting circuit, or by altering the number of turns of wire through which the existing current circulates around the field-magnet.

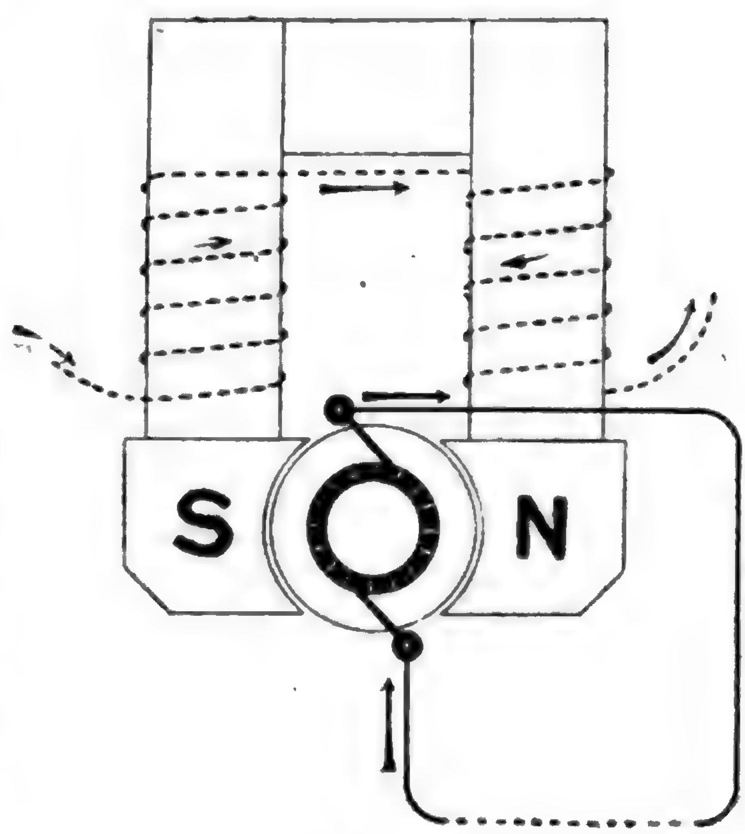


FIG. 40.—THE SEPARATELY-EXCITED DYNAMO.

The elementary methods of making dynamos self-exciting are three in number: (1) the whole current from the armature may be carried through field-magnet coils that are connected in series with the main circuit; (2) a portion of the current from the armature may be diverted from the main circuit and carried through field-magnet coils of somewhat high resistance connected as a shunt; (3) the current required to excite the field-magnet may be procured either from a second armature revolving in the same field, or (if the armature consists of many coils) from some of the coils of the armature that may be separately joined up for that purpose.

Series Dynamo.—The series-wound, or ordinary dynamo

(Fig. 41), possesses but one circuit. It has the disadvantage of not starting action until a certain speed has been attained, or unless the resistance of the circuit is below a certain limit; the machine refusing to magnetize its own magnets when there is too much resistance and too little speed. The least speed of self-excitation is a measure of the goodness of the magnetic circuit. Series-wound machines are also liable to become reversed in polarity, a serious disadvantage, and one that unfits this type of machine for employment in electro-plating or for charging accumulators. Any increase in the resistance of the series-wound dynamo lessens its power to supply current, because it diminishes the current in the coils of the field magnet, and therefore diminishes the amount of the effective magnetism. When lamps are in series (as is usual in an arc-light circuit) in the circuit of a series-wound dynamo, the switching on of an additional lamp both adds to the resistance of the circuit and diminishes the power of the machine to supply current. On the other hand, when lamps are in parallel across a pair of mains fed by a dynamo, if that dynamo is series-wound, the switching on of additional lamps not only diminishes the resistance of the circuit, but causes the field-magnets to be further excited by the increased current, so that the more lamps are on the greater becomes the risk of their getting too great a current.

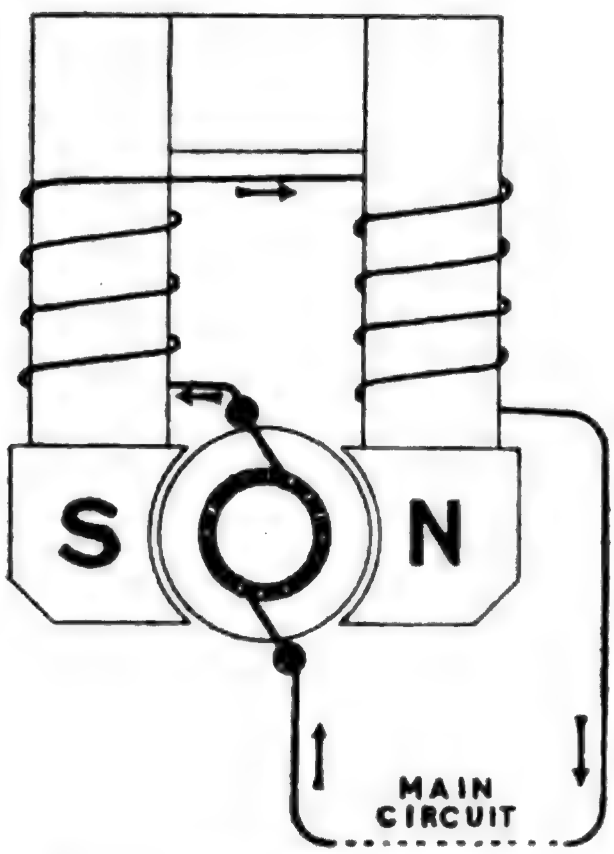


FIG. 41.—THE SERIES DYNAMO.

Shunt Dynamo.—In the shunt-wound machine (Fig. 42) the field-magnet is wound with many turns of fine wire, to receive only a small portion of the whole current generated in

the armature. These coils are connected to the brushes of the machine, and constitute a by-pass circuit or shunt. Shunt machines are less liable to reverse their polarity than series machines. Owing to the somewhat greater cost of the fine wire of the shunt coil, they are slightly dearer in prime cost than series machines of equal power, but the expenditure of electric energy to keep up the magnetism is alike in both cases. It requires the same expenditure of electric energy to magnetize an electromagnet to the same degree, whether the coil consists of many turns of thin wire or of a few turns of thick wire, provided the weight of copper used in the coil be alike in the two cases. When a shunt machine is supplying lamps in parallel, the addition of lamps which brings down the nett resistance of the circuit will increase the current, but not proportionally, for when the resistance of the main circuit is lowered, a little less current goes round the shunt and the magnetism drops a trifle; nevertheless, such a machine may regulate itself tolerably well if the internal resistance of its armature is very small. For a set of lamps in series, the power of a shunt dynamo to supply the needful current increases with the demands of the circuit, since any added resistance sends additional current round the shunt in which the field-magnets are placed, and so makes the magnetic field more intense. The electromotive-force of the shunt machine can be controlled by introducing a variable resistance into the shunt circuit.

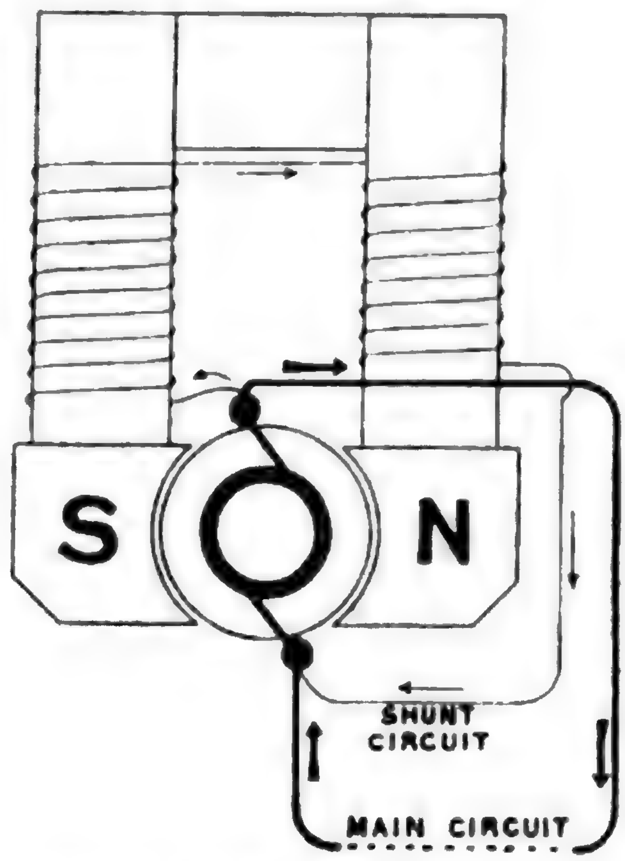


FIG. 42.—THE SHUNT DYNAMO.

A variety of the shunt method involves the use of a *third*

brush, placed against the commutator at some point intermediate between the points of highest and lowest potential. The ends of the exciting coil are connected to the third brush and to one of the ordinary brushes, so that the exciting coil receives a fraction of the volts generated in the armature.

Separate-circuit Self-exciting Dynamo.—There is yet a third species (Fig. 43) of self-exciting machine, in which the field-magnet coils are arranged to form part of a circuit entirely separate from the main circuit, but are supplied with currents from coils rotating in the field. There are two ways of carrying this into effect: (1) a second armature may be made to rotate between the same field-magnets in order to supply the exciting current, each armature having its own commutator; (2) a few of the armature coils may be connected up separately to a special commutator to supply an exciting current. Holmes, about the year 1868, described a machine having twenty helices in the armature, ten of which supplied alternate currents to the lamps, whilst the remaining ten, or any part of them, could be so connected up through a special commutator as to supply the exciting current to the field magnets. Ruhmkorff attained the same end by winding a second wire upon the Siemens (shuttle-wound) armature, which then was provided with a commutator at each end. The effect of the separate-coil method of excitation is almost identical with that of the shunt method, but it has the advantage that the current thus

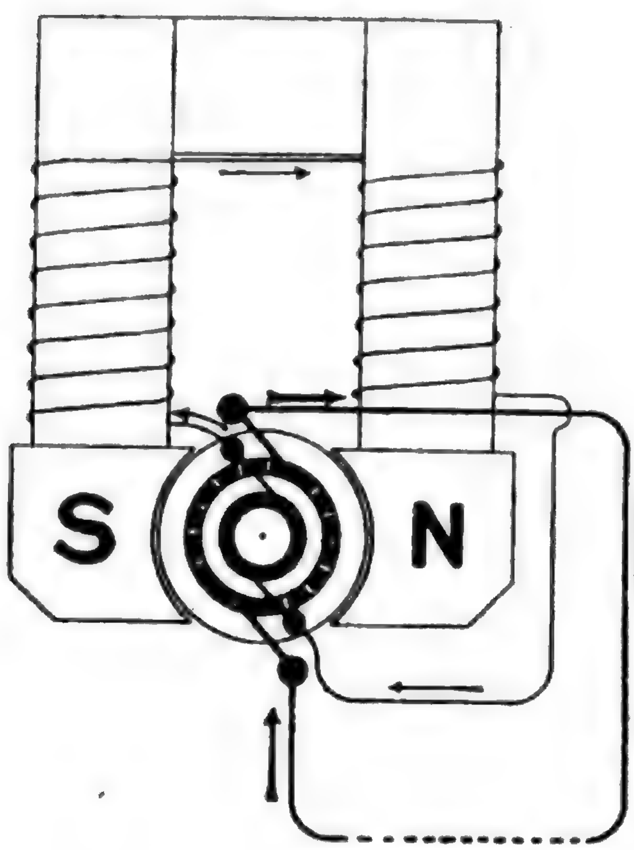


FIG. 43.—SEPARATE-CIRCUIT SELF-EXCITING DYNAMO.

taken off for magnetizing may be taken at a low voltage; this being preferable in the case of machines for high voltages. For machines working at 1000 volts and over, the cost of the fine wire for winding a shunt would be prohibitive.

Any of the five systems enumerated may be applied in continuous-current machines. For alternate-current machines, neither series-winding nor shunt-winding is applicable. Each of these five systems of exciting the field magnetism has its own merit for special cases, but none of them is perfect. Not one of these methods[1] will ensure that, with a uniform speed of driving, either the electric pressure at the terminals or the current shall be constant, however the resistances of the circuit are altered.

If all the lamps in the circuit of a dynamo were required to be kept alight, all being turned on and turned off at once—in other words, if the output of the machine were constant—it would matter little how the magnetism of the field-magnet was excited, whether in main circuit or in shunt, provided the speed were kept constant. But for systems with a variable number of lamps, none of the simple methods of excitation enumerated above will insure regularity of pressure in the electric supply.

Thanks, however, to the invention of combinations of windings, machines can be made which, when driven at a constant speed, give out their current at a constant pressure. These methods are carefully developed in Chapter XI. They are briefly described here also, so as to complete our summary of the methods of exciting the field-magnets.

COMBINATION METHODS.

There are two distinct cases for which self-regulation is required.

As the function of a dynamo is to feed with sufficiency and regularity a system of lamps, and as those lamps are

[1] An exception exists in the case of a shunt-wound machine if provided with Sayers' special device for enabling the brushes to be set with a backward lead. See Chapter XVI. on dynamo design.

usually in practice[1] arranged either in parallel or in series, it is clear that in the former case *a constant electric pressure* or *difference of potentials* between the mains, and in the latter *a constant current* is required.

Suppose a dynamo to have an armature of zero internal resistance, without demagnetizing reactions, and to have its field-magnets excited from some independent constant source. At a constant speed it would give a constant potential at its terminals whatever the resistance in the circuit. But if it has internal resistance, the external pressure will be less than the whole electromotive-force, and the discrepancy will be greater according as the internal resistance and the current are greater. Any resistanceless, separately-excited, or shunt dynamo would thus be self-regulating. The drop in the volts due to internal resistance and to armature reaction is nearly proportional to the current taken from the machine, being large when the current is large, and small when the current is small. Hence we may arrange to compensate these effects by an increase of the magnetism that shall also be proportional to the current. This is done by winding on the field magnet a few turns of thick wire to carry the current on its way from the armature to the lamps. It will then give, within certain limits, a constant difference of potentials at its terminals. For distribution *at a constant pressure*, we must have, therefore, dynamos in which there is a combination of *series* coils with some auxiliary independent constant excitation.

It has been hitherto found impracticable to devise any mode of compound winding which will be self-regulating for a constant current. Other modes of regulation are resorted to in the case of machines for series arc lighting for which an unvarying current is needed. These are considered in Chapters XVIII. and XXIX.

[1] Occasionally incandescent lamps are arranged with two, three or more lamps in series, a number of such series being united in parallel across mains that are kept at a constant pressure. Less frequently a few lamps all in parallel with one another are inserted in the circuit of a series of arc lamps through which a current of constant strength is maintained. In any case, distribution must fall under one or other of the two cases considered.

COMBINATIONS TO GIVE CONSTANT PRESSURE.

The following combinations are all possible solutions of the problem of giving current at a constant pressure:—

(1) *Series and Separate* (Deprez).—A separate and constant excitation is provided from some independent source, so as to bring up the volts on open circuit to the required pressure. The additional excitation needed to raise the magnetism, so as to compensate the lost volts and the armature reaction, is provided by an additional series winding, as indicated in Fig. 44.

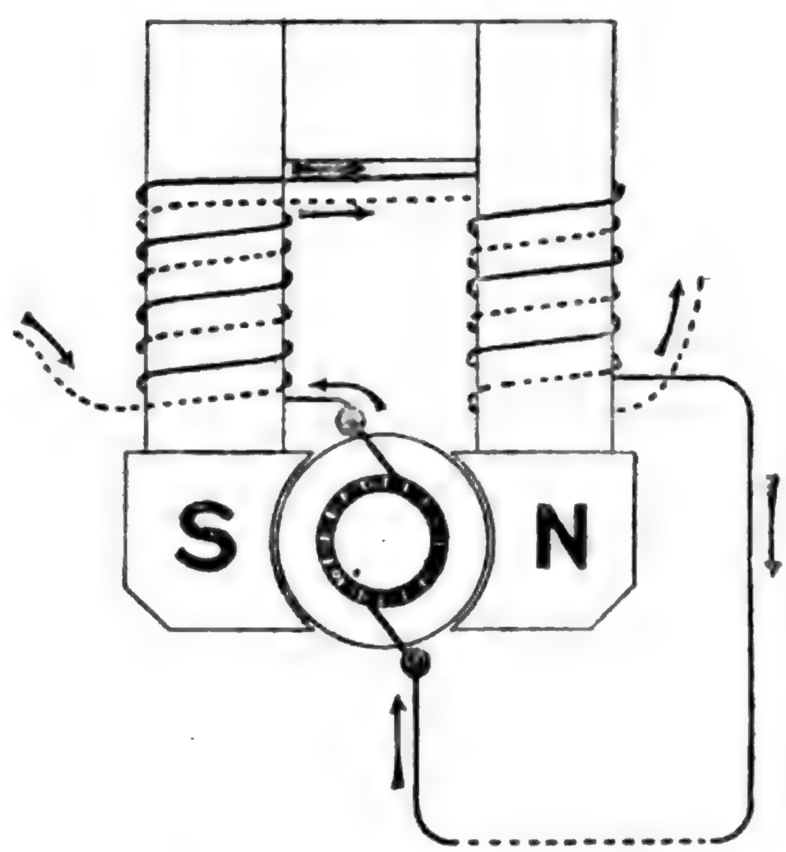


FIG. 44.—COMBINATION OF SERIES AND SEPARATE.

(2) *Series and Magneto* (Perry).—The initial excitation may be that of a permanent magnet of steel: but Professor Perry suggested the more general solution of introducing into the circuit of a series dynamo a separate magneto machine also driven at a uniform speed, such that it produces in the circuit a constant electromotive force equal to the pressure which it is desired should exist between the leading and return mains. The series machine only operates to give the additional volts needed for compensating the losses.

The combination of a permanent magnet with electromagnets in one and the same machine, is much older than the

suggestions of either Deprez or Perry, having been described by Hjorth in 1854.

(3) *Series and Shunt.*—A dynamo having its coils wound as in Fig. 45, so that the field-magnets were excited partly by the main current, partly by a shunt current diverted from the main circuit, was used by Brush[1] as early as 1878. His machine was very nearly self-regulating, there being less than one volt of variation in the pressure within a wide range of current. The voltage will depend upon the degree to which the magnetism is excited when the shunt is acting alone on open circuit. The arrangement with shunt and series coils is commonly known as a *compound winding.*[2]

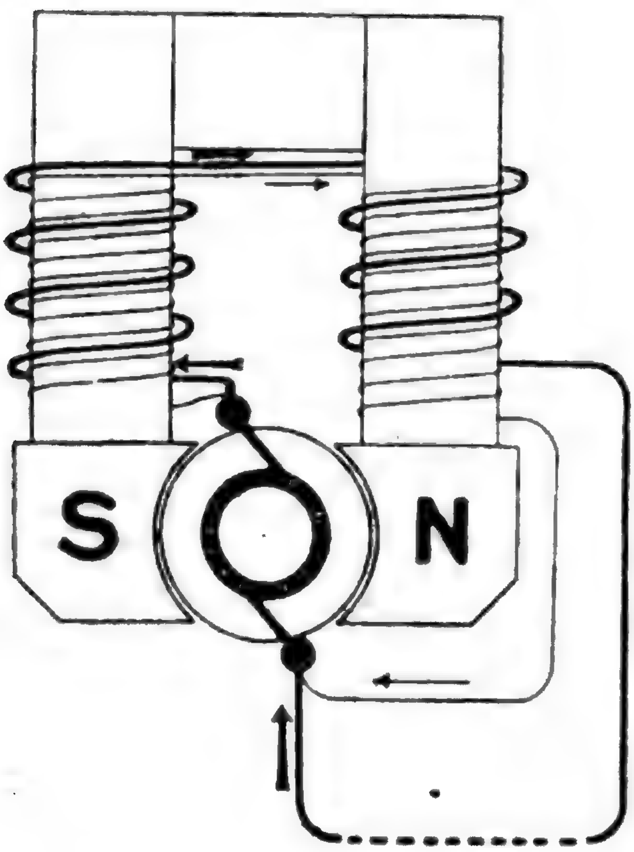


FIG. 45.—SERIES AND SHUNT.

(4) *Series and Long Shunt.*—In 1882 the author proposed to give this name to a combination closely resembling the preceding. If the magnets are excited partly in series, but also partly by coils of fine wire, connected as a shunt not across the brushes but

[1] The shunt part of the circuit, originally called the "teazer," was adopted at first in machines for electroplating, with the view of preventing a reversal of the current by an inversion of the magnetization of the field-magnets, but was retained in some other patterns of machine on account of its usefulness in "steadying" the current.

[2] The invention of the "series and shunt" winding is claimed for several rivals. Brush undoubtedly first used it commercially, but whether with any knowledge of all its advantages is doubtful. It has also been claimed by Mr. S. A. Varley on the strength of the machine described in his patent specification, No. 4905 of 1876, in which there were two circuits, of different resistance, both having coils wound on the field-magnets, and both going to the lamp. He has obtained a decision in the law courts that this strange arrangement anticipated

across the terminals of the external circuit, then the pressure at the terminals should be still more constant.

(5) *Series and Separate-coil.*—This method is not much used. For alternate-current dynamos a modification of it has been used with success, the "series" or main-circuit excitation being, in this case, replaced by an excitation derived from the main current by means of a small transformer, and rectified by a commutator.

that described by Brush. Compound winding was, however, described in 1871 by Sinsteden, in *Pogg. Annalen* (*Supplement-Band*, v.), 651. It was mentioned as having some advantages by Sir C. W. Siemens in *Philosophical Transactions*, March 1880. It is also claimed for Lavckert (see note by M. Boistel, p. 100 of his translation of first edition of this work); Paget Higgs, (*Electrical Review*, xi. 280, and *Electrician*, Dec. 23, 1882); J. W. Swan, see Bosanquet (*ib.*, Dec. 9, 1882; J. Swinburne (*ib.*, Dec. 23, 1882); S. Schuckert (*ib.*, Oct. 13, 1883). It is claimed in America by Edison; and it has been patented by Messrs. Crompton and Kapp (*ib.*, June 9, 1883). See also Hospitalier (*L'Électricien*, No. 20, 1882). Students should also consult a series of articles in *The Electrician*, vol. x., beginning Dec. 16, 1882, by Mr. Gisbert Kapp. Further, they should see a paper by Dr. Louis Bell in the *Electrical World*, xvi. 383, 1891.

CHAPTER IV.

ACTIONS AND REACTIONS IN THE ARMATURE.

In this chapter we deal mainly with continuous-current dynamos having armatures of either ring or drum type, and with a simple magnetic field such as is furnished by the two-pole field magnet so common in machines of this class. Many of the considerations apply equally to the case of multipolar machines, to machines with armatures of the disk type, and to alternate-current machines.

For the sake of clearness we will suppose the armature (as viewed from the end to which the commutator is affixed), to be rotating right-handedly; and we will further suppose that the north pole of the field-magnet is situated on the right hand, as in Figs. 39 to 45, so that the magnetic lines pass through the armature core from right to left. We shall further suppose that the coils on the armature cores are wound right-handedly. Taking this as a standard case it is afterwards very easy to see how a change in any one of these conditions will affect the induction of electromotive-force.

In Fig. 46 these points are illustrated by an end view of a ring armature. The magnetic lines proceeding from the N-pole will cross the adjacent gap-space from right to left, and enter the iron core of the armature; traversing this (as illustrated in Fig. 60, p. 72), they will then pass across the other gap-space on the left and enter the S-pole of the field magnet. The copper wires or conductors of the armature, as each rises successively in the left-hand gap, will cut these magnetic lines. Each conductor will emerge at the top of the gap, will move over the highest part of the armature from left to right, and in descending the gap-space on the right

will again cut the magnetic lines. If we now apply the rule concerning induction[1] laid down on p. 22, we shall find that the directions of the induced electromotive forces in these rotating conductors will be as follows :—In all the conductors as they *ascend* through the left-hand gap-space, the direction of the induced electromotive-force is *toward* the observer—whilst in all those that are *descending* the other gap-space on the right the induced electromotive-forces will be directed *from* the observer. If we assume that these electromotive-forces are actually producing currents,[2] then we may say that the currents flow toward the observer in the conductors which are rising in the left gap-space; and from the observer in those that are descending the right gap-space. If the arma-

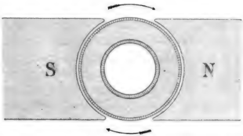


FIG. 46.—END VIEW OF RING ARMATURE BETWEEN TWO-POLE FIELD MAGNET.

ture is wound as a ring, the currents which come in one direction in the gap-space return in the other direction down the inside of the ring. If the armature is wound as a drum, then the currents simply cross at the end of the core through connecting conductors provided for the purpose.

Now consider the way in which the coils on the armature are connected together. Whether wound as ring or drum

[1] See footnote, p. 1.

[2] In all dynamos, when used as *generators*, the currents being set up by the electromotive-forces are of course in the *same direction* as the electromotive-forces which impel them. But it must be remembered that in the case of machines that are used as *motors* the currents are being sent in by superior electromotive-forces from outside, and that the induced electromotive-forces in the motor's armature are always in an *opposite direction* to that of the current that is flowing.

they are grouped symmetrically around a symmetrical core, and united together into one closed coil; whilst at regular intervals along the windings, connecting pieces lead down to the separate bars of the commutator. Fig. 34, p. 40, shows a simple ring winding, consisting of 32 turns of wire grouped in eight "sections" or groups, each consisting of four turns. The end of each section is joined to the beginning of the next, all the way round. There are eight bars in the commutator, and each section of the winding is connected down at its ends to two adjacent bars of the commutator. In Fig. 34 the brushes are represented as making contact respectively with the highest and lowest bars of the commutator. As the windings on the ring are right-handed, a little consideration will show, in accordance with the preceding paragraphs, the induced currents in the ascending windings on the left-hand half of the ring will all be climbing from the lowest point to the highest; and also the currents in the right-hand half of the ring will also be climbing from the lowest point to the highest. These two currents will unite at the top bar of the commutator, and will flow together into the upper brush (which will accordingly be deemed the positive brush), and thence will go to supply the external circuit; after which the current will return to the lower, or negative brush, and will there re-enter the armature at the lowest bar of the commutator, dividing again into two parts and flowing up the two halves of the winding as before. If the conductors on the armature were wound (or connected) left-handedly, the lower brush would be the positive one, and the upper the negative. All the preceding argument would equally apply to a drum-winding (compare p. 245), but, owing to the overlapping of the two halves of the windings, the paths of the currents would not be quite so obvious.

It will be noted that the current, after having entered the armature coils and divided into its two paths, goes from section to section without going down into any of the commutator bars, until both streams unite at the other side and pass down into the bar of the commutator which is for the moment passing under the brush. At those moments when one of the

commutator bars is just leaving contact with a brush, and another one is coming into contact with it, the brush will rest on two adjacent bars and will momentarily short-circuit one section of the coils. While this lasts the two streams that come through the two halves of the winding will flow respectively to the two bars of the commutator, and will thus unite by both flowing into the same brush. It is obvious that if a current is introduced at any point into a closed circuit (such as the winding of a ring) and is taken out at any other point, there must be two paths through the windings. In the case of multipolar machines we shall see there are in many cases more than two paths, the current bifurcating more than once in its way through the armature.

It is evident that if the magnetic lines in the gap-space are more closely crowded together in one part than in another, the electromotive-forces induced in the separate windings as they cut these magnetic lines will be of unequal amount; the greatest electromotive-force being generated in those conductors which are passing through that part of the magnetic field where the lines are crossing the gap most densely. But since the individual conductors are all united together end to end, it will be obvious that the total electromotive-force of either half of the winding, from brush to brush, will be the sum of the electromotive-forces in the separate coils.

Induction in a Uniform Horizontal Magnetic Field.

In considering the case of an ideal simple dynamo, it was shown that the induction in the rotating loop or coil was zero at the position where it lay in the diameter of commutation, and that the induction increased (as the sine of the angle) to its maximum value at about 90° (see Fig. 18, p. 32). This is of course true for the ideal case of the magnetic lines going straight across horizontally with equal density everywhere. In actual dynamos the distribution of magnetic lines in the gap is different, not always symmetrical, as we shall see.

Returning to the ideal case, Fig. 47, which presents a curve of *sines*, will serve to represent, by the height of the curve the amount of induction going on in an armature at every 10° round the circle. If there are, for example, thirty-six sections in a ring armature, so that the sections are spaced out at 10°

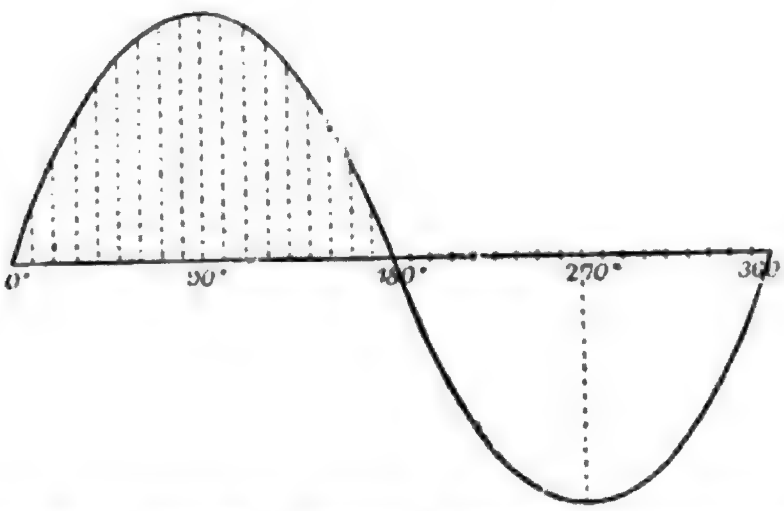


FIG. 47.—CURVE OF INDUCED ELECTROMOTIVE-FORCE.

apart, the least active sections will be those at 0° and 180°, whilst the most active are those at 90° and 270°. But in all the ordinary "closed-coil" armatures, the separate sections are connected together so that any electromotive-force induced in the first section is added on to that induced in the second, and that in the third is added to these two, and so on all the way round to the brush at the other side. The separate electromotive-forces are added together just as are the separate electromotive-forces of a battery of voltaic cells united in series. A ring of battery cells united in series, like Fig. 48, but having one-half the cells set so that the current in them tends to run the other way round the ring, forms a not inapt illustration of the induction in the sections of a ring armature.

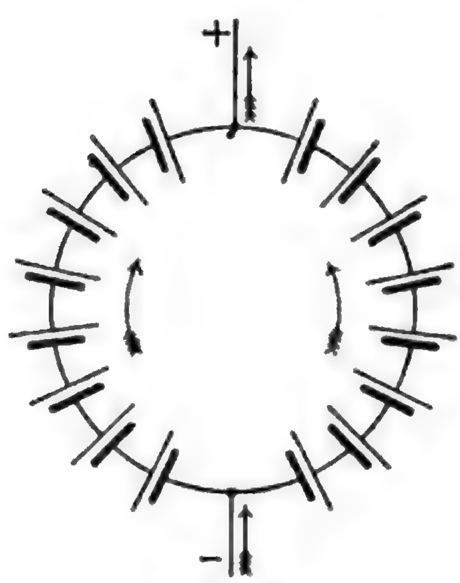


FIG. 48.

Now, knowing how the induction in individual coils or sections rises or falls round the ring, let us inquire what this

will result in when we add up the separate electromotive-forces so as to find the total effect. We shall have to add up the effects of all the sections round, from the negative brush at $0°$ on one side, to the positive brush at $180°$ on the other side: and the result will be the same in each half of the ring because of symmetry. Suppose we take the side from $0°$ by $90°$ to $180°$ (on the left in Figs. 20 and 46). If we look at the curve given above (Fig. 47) we shall see that as the heights of the dotted lines represent the amount of induction, the total effect will be got by adding up the lengths of all those from $0°$ to $180°$; and of course the sum is equal to the sum of the negative lengths between $180°$ and $360°$. But we may do the thing in another way, which, besides giving us the final total, will show us how the sum grows as each length is successively added on. We should find that the sum grew slowly at first, then rapidly, then slowly again as it neared its highest value. The sum of the effects would grow, in fact, in a fashion represented on a reduced scale in the curve of Fig. 49. This process of adding up a continuously varying set of values is called by mathematicians integrating. Fig. 49 is got by integrating the values of the curve Fig. 47 between the limits of $0°$ and $180°$. Now in the actual dynamo this integration is effected by the nature of things, in consequence of the fact that each section is united to those on either side of it.

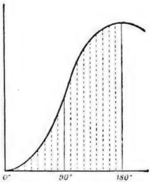


FIG. 49.—INTEGRATED CURVE OF POTENTIALS.

It is possible to investigate by experiment[1] either the

[1] For some investigations made by the author, the reader is referred to the author's *Cantor Lectures* delivered in 1883 before the Society of Arts, and which are also described in the earlier editions of this book. The reader should refer to curves of induction obtained by Gaugain (see *Annales de Chimie et de Physique*, 1873), and by Isenbeck (see *Elektrotechnische Zeitschrift*, Aug. 1883). The more recent researches are referred to on p. 65, and in the Chapter on Alternators.

induction in the individual coils or the total integrated potential. Several methods have been suggested for measuring the electromotive-forces.

Method of Exploring Brushes.—The electromotive-force induced in a single section as it passes any particular position, may be examined by means of a voltmeter in the following way. Two small metal brushes are fixed to a piece of wood at a distance apart equal to the width between two consecutive bars of the commutator. These brushes are united by wires to the voltmeter terminals. The two brushes are placed against the commutator, as shown in Fig. 50, while it rotates; and as they can be applied at any point, they will measure the average volts in that section of the armature which is passing through the particular part of the field corresponding to the position of the contacts.

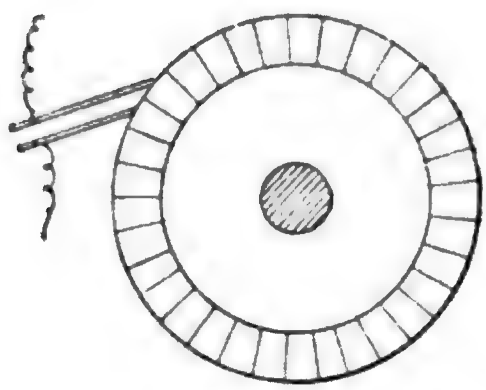


Fig. 50.—Method of Experimenting at Commutator of Dynamo.

Mordey's Method.—The rise of the totalized (*i. e.* "integrated") potential round the armature can be measured experimentally by a method first suggested by Mr. W. M. Mordey, involving the use of a single exploring brush and a voltmeter. One terminal of the voltmeter is connected to one of the brushes of the dynamo (Fig. 51), and the other terminal is joined by a wire to a small pilot brush *p*, which can be pressed against the rotating collector at any desired part of its circumference. In a well-arranged continuous-current dynamo, if one thus measures the difference of potential between the negative brush and the successive bars of the commutator one finds that the potential increases regularly all the way round the armature, in both directions, becoming a maximum at the opposite side where the positive brush is. The distribution is irregular in badly designed machines.

Swinburne's Method.—An elegant modification of the preceding method consists in connecting a high-resistance wire across the terminals of the machine, and finding by a

detector galvanometer the position along this wire of the points which have the same potential as that of the pilot-brush on the commutator. Being a zero method it is very accurate; and it dispenses with the voltmeter, which for the preceding method needs to be accurate over a wide range.

Joubert's Method.—Another mode of examining the electromotive-force induced at every successive point in the

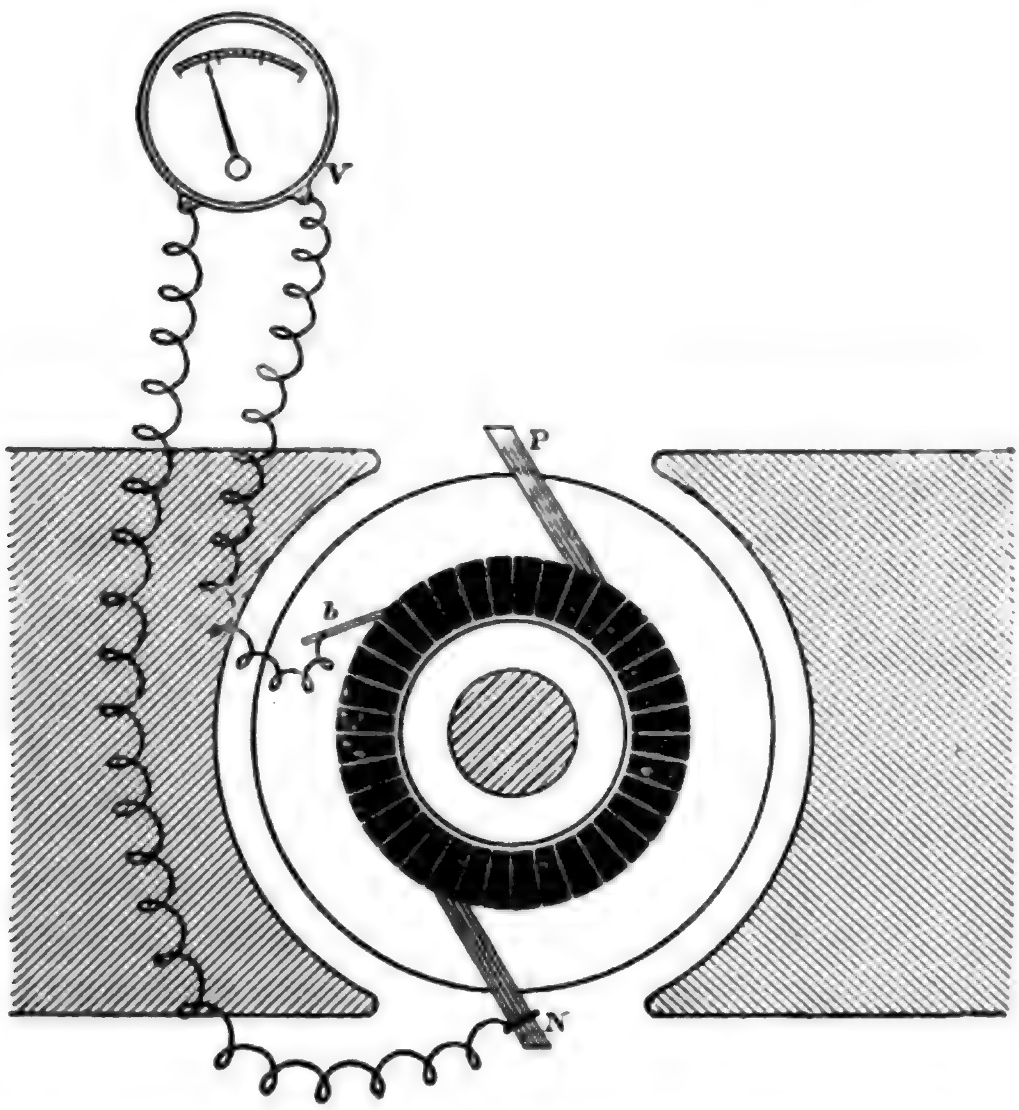


FIG. 51.—MORDEY'S METHOD OF EXPLORING THE POTENTIALS AROUND THE COMMUTATOR.

rotation was devised by M. Joubert,[1] who placed on the shaft of the dynamo a pair of insulated metal collars connected to the ends of the armature winding; each collar having a projecting contact-piece which at each revolution made a moment contact against a spring. The moment at which this occurred

[1] *Annales de l'École Normale*, x. 131, 1881.

depended upon the position of the contact springs, which could be adjusted to different points, and thus enable measurements to be made of the instantaneous values of the electromotive-force at all different positions of the armature. Joubert's method has been used, with some modifications, by Mordey and Raworth,[1] by Ryan,[2] and by Fleming.[3]

Mordey's Statical Method.—Another method, applicable to machines at rest and without currents in the armature, consists in separately exciting the field-magnets, while the armature coils, or any one of them, are connected to a suitable ballistic galvanometer, and observing the throw caused by the sudden turning off of the current in the exciting circuit. If this is done in a number of successive positions of the arma-

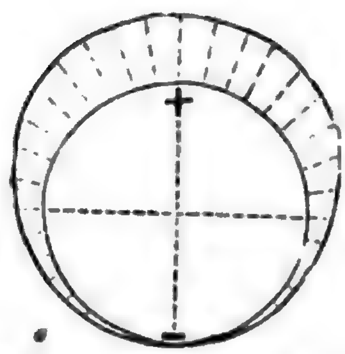


FIG. 52.—DIAGRAM OF POTENTIAL ROUND THE COMMUTATOR OF GRAMME DYNAMO.

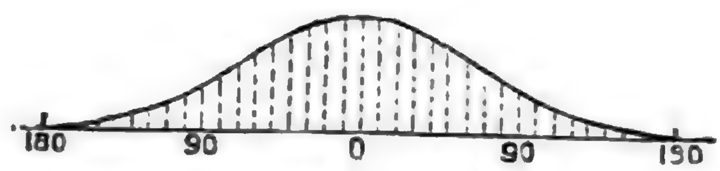


FIG. 53.—HORIZONTAL DIAGRAM OF POTENTIALS AT COMMUTATOR OF GRAMME DYNAMO.

ture, relatively to the field-magnet, a measure is obtained of the density of the magnetic flux, corresponding to each position of the armature, and the result may be plotted out in a curve exhibiting the distribution of magnetism in the field. This distribution is, however, perturbed, as we shall see, when the machine is running by the current in the conductors of the armature.

These indications may with advantage be plotted out round a circle corresponding to the circumference of the commutator. Figs. 52 and 53, which are reproduced from the author's

[1] *Journal Inst. Electrical Engineers*, xviii. 670, 1889.
[2] *Trans. Amer. Instit. Electrical Engineers*, vii. 3, 1890.
[3] *Electrician*, Feb. 22, 1895.

Cantor Lectures of 1883, serve to show how the potential in a good Gramme machine rises gradually from its lowest to its highest value.

It will be seen that, taking the negative brush as the lowest point of the circle, the potential rises perfectly regularly to a maximum at the positive brush. The same values as are plotted round the circle in Fig. 52 are also plotted out as vertical ordinates upon the level line in Fig. 53, which is an actual record taken from an "A" Gramme.

Such curves, plotted out from measurements of the distribution of potential at the commutator, show not only where to place the brushes to get the best effect, but enable us to judge of the relative "idleness" or inductive activity of coils in different parts of the field, and to gauge the actual density of different parts of the field while the machine is running The steepness of the slope of the curve at different points is itself a measure of the relative idleness or activity of coils in the corresponding parts of the field.

The rise of potential is not equal between each pair of bars, otherwise the curve would consist merely of two oblique straight lines, sloping right and left from the points of highest and lowest potential respectively. On the contrary, there is very little difference of potential between the commutator bars corresponding to the coils that are relatively idle. The greatest difference of potential occurs where the curve is steepest, at a position nearly 90° from the brushes, in fact, at that part of the circumference of the commutator which is in connexion with the coils that are passing through the position of best action. If the magnetic field in which the armature rotated were uniform and parallel, the curve would be a true "sinusoid," or curve of sines. The number of magnetic lines that pass through a coil would be proportional to the cosine of the angle which the normal of that coil makes with the resultant direction of the magnetic lines in the field, and the rate of cutting the magnetic lines should be proportional to the sine of this angle. Now the cosine is a maximum when the angle $= 0°$ and the sine is a maximum when the angle $= 90°$; hence the rate of increase of potential should be

at its greatest when the coil is parallel to the magnetic lines—as is very nearly realized in the diagram of Fig. 53, which, indeed, is very nearly a true "sinusoidal" curve.

But in ordinary dynamos with polar surfaces that embrace the armature closely on both sides (as in Fig. 46, p. 59) the field is—at least when not distorted by armature reactions—distributed nearly radially in the gap spaces; and in the parts lying between the pole tips there are hardly any magnetic lines entering or leaving the armature. Hence in such a case the revolving conductors become active as they plunge into the gap, continue nearly equally active as they pass along the gap, and become almost idle when they emerge to pass between the pole-tips. In such a case the result of exploring the potentials by the first method will be to yield a curve such as A in Fig. 54. The corresponding curve for the total potential measured from the negative point around the commutator by the second method is indicated at B in Fig. 54.

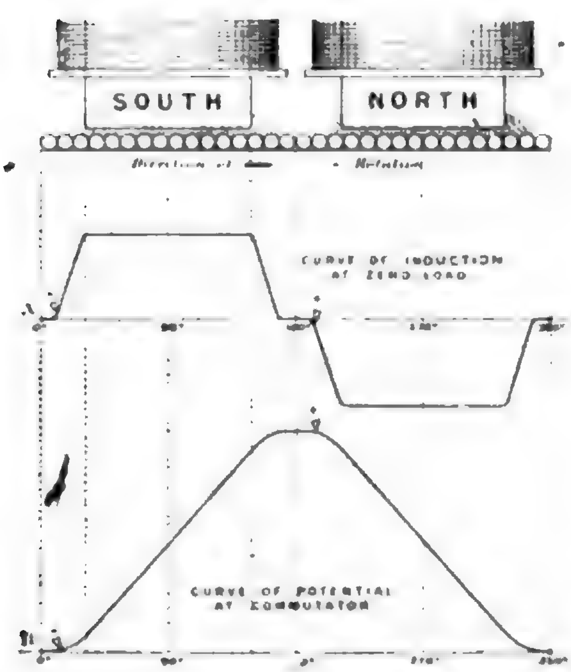


FIG. 54.

If the brushes are badly set, or if the pole-pieces are not judiciously shaped, the rise of potential will be irregular, and there will be maxima and minima of potential at other points. An actual diagram, taken from a dynamo in which these arrangements were faulty, is shown in Fig. 55, and again is plotted horizontally in Fig. 56; from which it will be seen, not only that the rise of potential was irregular, but that one part of the commutator was more positive than the positive brush, and another part more negative than the negative. The brushes, therefore, were not getting their proper difference of potential; and in part of the coils the currents were actually being forced against an opposing electromotive-force.

As we shall see, the current in the armature reacts on the magnetic field, and distorts the distribution of magnetic lines in the gap-space.

These methods of exploring the distribution of potential round the commutator have proved very useful in practice, and elucidated various puzzling and anomalous results found by experimenters who have not known how to explain them.

Curves similar to those given can be obtained from the commutators of any continuous-current dynamo having a closed-coil armature. The open-coil machines used in arc lighting give widely different curves owing to the peculiar

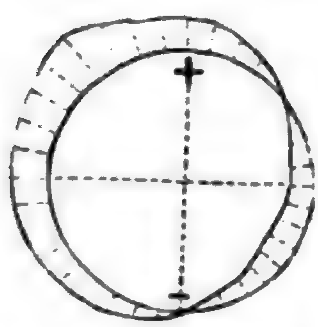


Fig. 55.—Diagram of Potential round the Commutator of a badly arranged Dynamo.

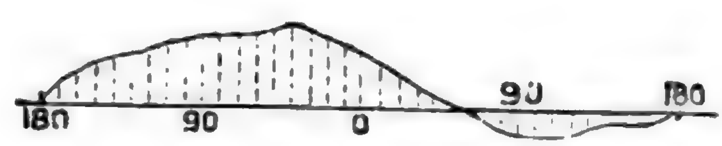


Fig. 56.—Horizontal Diagram of Potentials at Commutator of Faulty Dynamo.

arrangements of their commutators. It should also be remembered that the presence of brushes drawing a current will alter the distribution of potential; and the manner and amount of such alteration will depend on the position of the brushes, as well as on the amount of current drawn and the design of the machine.

Curves showing the actual distortions due to the armature reaction, have been given by von Gaisberg [1] for a Schuckert dynamo, by Kohlrausch [2] for a Lahmeyer dynamo, and by M. E. Thomson [3] for a Thomson-Houston dynamo; also by Ryan (see above).

[1] *Elektrotechnische Zeitschrift*, vii. 67, Feb. 1886.
[2] *Centralblatt für Elektrotechnik*, ix. 419, 1887.
[3] *Electrical World*, xvii. 392, 1891.

Reactions due to the Currents in the Armature.

When a dynamo is yielding a current, a set of entirely new phenomena arises in consequence of the magnetic and electric reactions set up between the armature and the field-magnets, and between the separate sections of the armature coils. The current circulating in the armature windings produces magnetizing effects which interfere with those of the exciting currents of the field-magnet. In addition to this there may also be eddy currents in the masses of metal which will perturb the magnetic field. The reactions of the running armature manifest themselves in several ways, the more important of which are (*a*) a tendency to cross-magnetize the armature; (*b*) a tendency to spark at the brushes; (*c*) hence the necessity of shifting the brushes through a certain angle to such a point that sparking disappears; (*d*) a consequent tendency for the armature current to demagnetize; (*e*) variations of sparking, and consequently of the neutral points, when the amount of current drawn from the machine is altered; (*f*) heating of armature cores and coils; (*g*) heating of the pole-pieces of the field-magnets; (*h*) a consequent discrepancy between the quantity of mechanical horse-power imparted to the shaft and the electric horse-power furnished in the electric circuit. The nature of these reactions demands careful attention.

Cross-magnetizing Effect of Armature Current.—We have seen (pp. 40, 62, and Fig. 48) that any closed-coil armature may be regarded as acting like a double voltaic battery, the two sets of coils acting like two rows of cells united in parallel. We have now to show that a ring armature may be regarded also as a double magnet. Suppose a semi-ring of iron to be surrounded, as in Fig. 57, by a coil

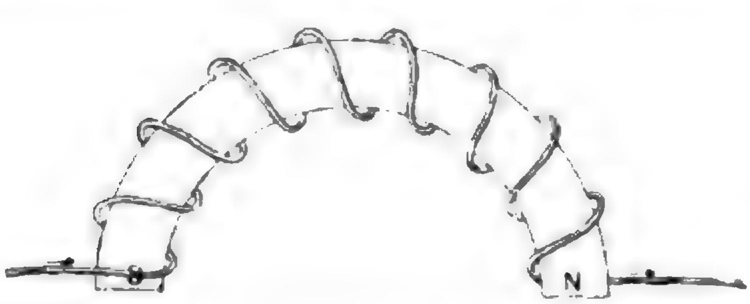


Fig. 57.—Poles on Half Ring.

carrying a current, it will become, as every one knows, a magnet having a N-pole at one end, and a S-pole at the other. If a complete ring be similarly over-wound, but with an endless winding, and if then electric currents from a battery or other source are introduced into this coil at one point, flowing round the two halves of the ring to a point at the other side, and then leave the coil by an appropriate conductor, each half of the ring will be magnetized. There will be, if the currents circulate as represented by the arrows in Fig. 58, a double (or "consequent") S-pole at the

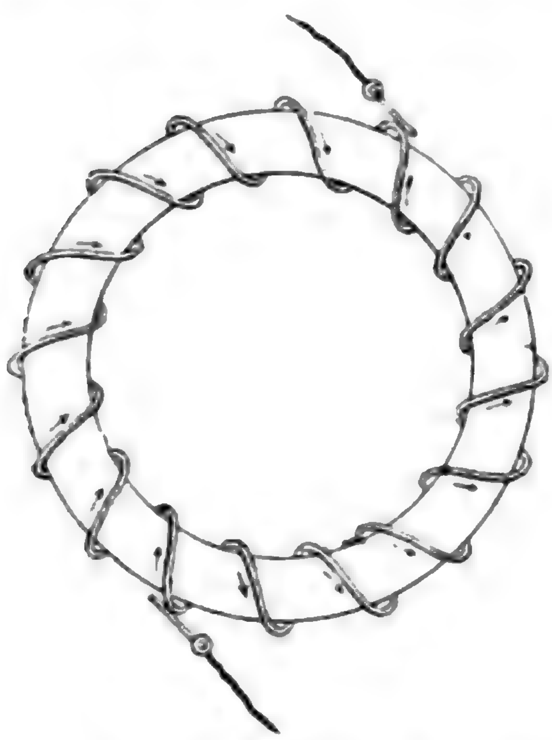


Fig. 58.—Circulation of Current around Ring Armature.

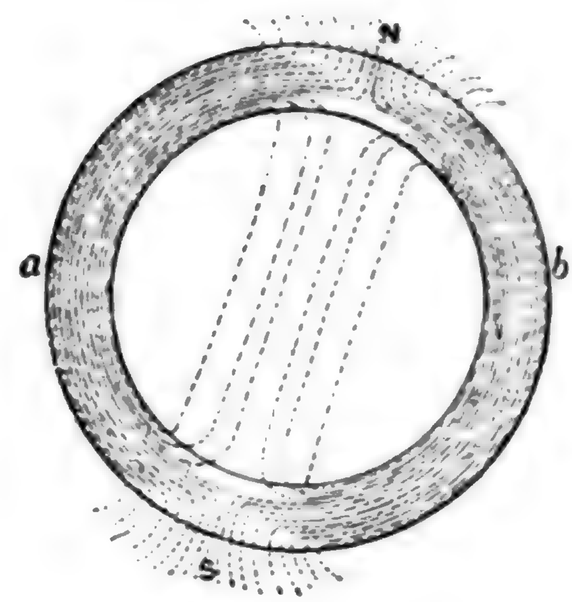


Fig. 59.—Magnetization due to Armature Current.

point where the currents enter the winding, and a double N-pole at the place where the currents leave. The currents circulating in a Gramme ring will therefore tend to magnetize the ring in this fashion. Let us see how such a magnetization is distributed inside the iron itself. Fig. 59 shows the general course of the magnetic lines as they permeate through the iron; where they emerge into the air are the effective poles of the ring regarded as a magnet. Fig. 59 should be very carefully compared with Fig. 65. It will be noticed that though the majority of the magnetic lines pass externally into the air at the outer circumference of the ring, a few of them find

their way across the interior of the ring, from its N to its S-pole. This part of the magnetic field would in an actual dynamo be deleterious if the number of magnetic lines were not in reality few. The presence of the external masses of iron at the polar parts of the field-magnet tends to cause these magnetic lines to find their way externally.

It is evident that this cross-magnetizing effect will produce a distortion of the magnetic field in the pole-pieces and in the gap-space. If, however, the brushes could be allowed to remain at the ends of a diameter exactly symmetrically between the pole-tips, the effect of the cross field upon the

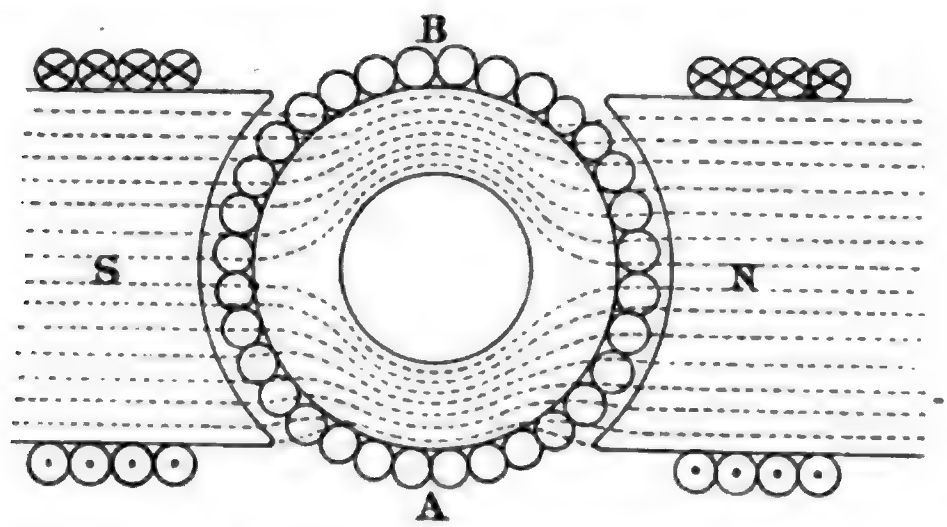


FIG. 60.—MAGNETIC FLUX THROUGH ARMATURE, WHEN NO CURRENT IS FLOWING.

electromotive-force would be inappreciable. But the brushes have to be displaced into an angular position in order to avoid sparking: the diameter of commutation being oblique when the brushes are moved forward to the neutral points. When this is done the armature current produces, as we shall see, not only a cross magnetizing effect, but also a demagnetizing effect; and this weakens the electromotive-force.

Fig. 60 represents[1] the magnetic flux through an armature at rest, when the field-magnets are separately excited. The width of the gap-space is exaggerated, and the conducting wires both on the armature and on the field-magnet are shown in section as if consisting of a single layer of large

[1] Figs. 60, 61, 62 and 68 are taken, with some modification, from Esson's paper in *Journal Inst. Electrical Engineers*, xix. 135, 1890.

round wires. Wires in which a current flows *toward* the observer are distinguished by a central dot. Wires in which a current flows *from* the observer are distinguished by a cross. The reader may think of the dot as representing the point of an arrow advancing towards him; whilst the cross may represent its retreating tail. Wires carrying no current are left blank. It will be noticed that the magnetic lines are fairly uniformly distributed both in the gap-spaces and in the polar portions of the field-magnet. The armature is drum-wound, the wires being only on the outside: the magnetizing effect of a current in it will be of the same kind as that traced

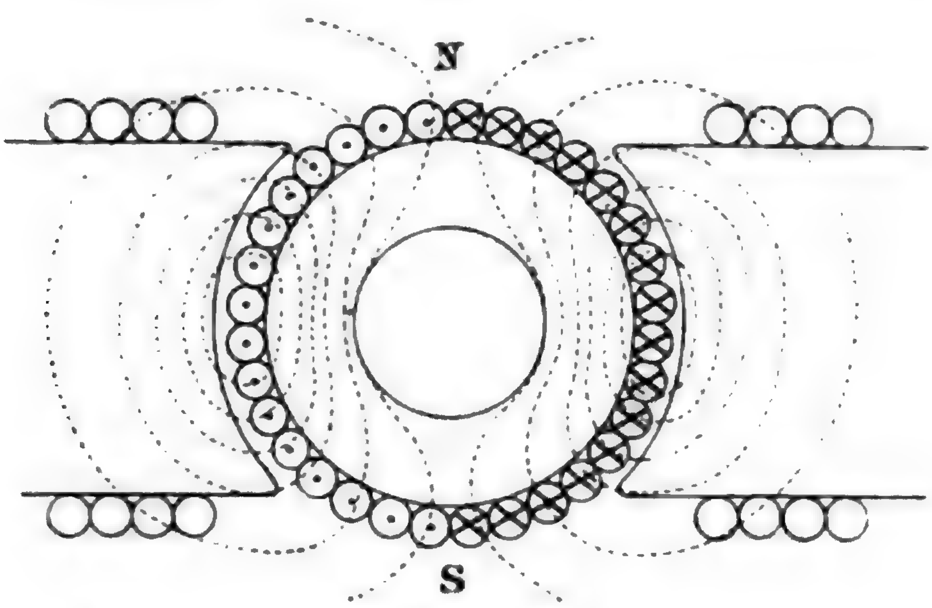


FIG. 61.—CROSS-MAGNETIZING EFFECT OF THE ARMATURE CURRENT.

out above in the case of a ring-wound armature, though less in degree.

Suppose, now, the exciting current in the field-magnet coils to be removed, and a current sent through the armature coils only, so as to imitate the effect of the current generated by the machine when running. If it is to do this, and if the armature connexions are in right-handed order, and the machine rotating right-handedly, the currents in both sets of windings will tend to climb toward the top, the upper brush being the positive brush, and the double pole created at B will be a north pole. Suppose the brushes by which the current enters and leaves to be set respectively at the highest and lowest points, as in Fig. 61; then the dotted lines may be

taken as representing the flow of magnetic lines due to the currents in the armature. Since the number of such magnetic lines depends upon the goodness of the magnetic path which they have to follow, it is clear that the cross field produced by a given current, flowing in a given set of conductors, will be greater the narrower the gap-space, and the wider the arc spanned by the polar masses of iron[1] on either side. It may also be noted that the cross-flux in either half of the armature must cross the gap-space twice.

But in an actual dynamo, when generating a current, both these magnetizing actions are going on at once. If we super-

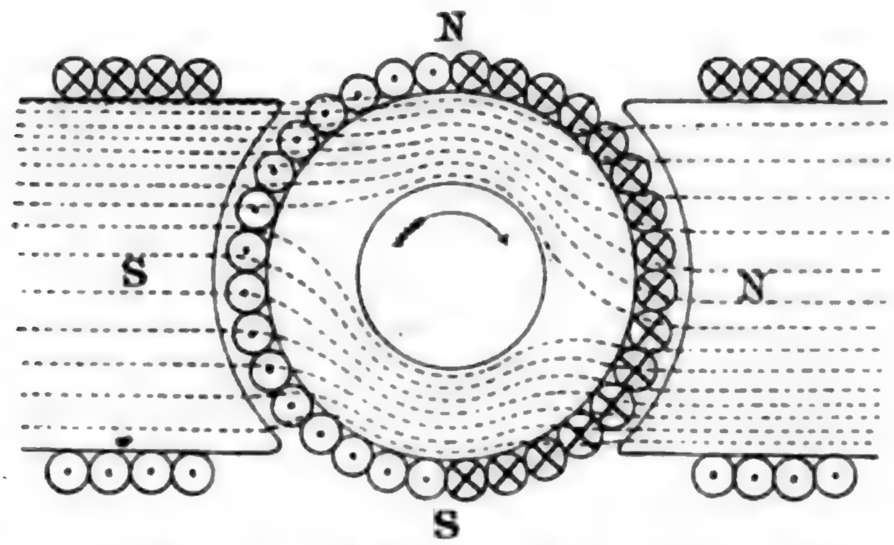


FIG. 62.—JOINT MAGNETIZING EFFECT OF CURRENTS IN FIELD-MAGNET AND ARMATURE (no lead).

pose Fig. 61 on Fig. 60 we shall obtain an approximate picture of the state of things, as Fig. 62. We supposed that the brushes were set to touch at two points on the vertical diameter. The field-magnets tend to magnetize the ring so that its extreme left point is a N-pole, and the currents tend to magnetize it so that its highest point, where the brush is, is a N-pole. The consequence of this will be a resultant magnetization in an oblique direction. The magnetism is thus distorted in the direction of the rotation (in motors it is distorted the other way) as if the rotation of the armature had actually dragged the magnetism round a little. The position of maximum potential will also be shifted a little in

[1] See *Journal Inst. Electrical Engineers*, xx. 290, 1891.

the direction of the rotation. Now for reasons to be shortly discussed, the brushes must be set, not on the diameter that lies symmetrically between the pole-tips, but at an angle a little ahead of this in the direction of the rotation. Hence the cross field will also lie obliquely, tending to further distortion.

Draw a line O F (Fig. 63) to represent the ampere turns due to the field-magnet excitation, and the line O B to represent, relatively in magnitude and direction, the ampere turns due to the armature current; then the diagonal O R will represent the direction and magnitude of the resultant magnetizing tendency.

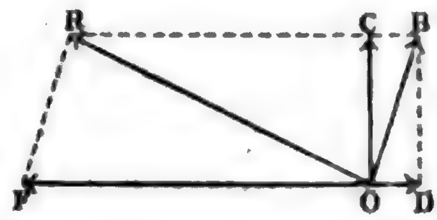


FIG. 63.

An exaggerated diagram of the distortions which result is given in Fig. 64, which relates to a ring-wound dynamo. A

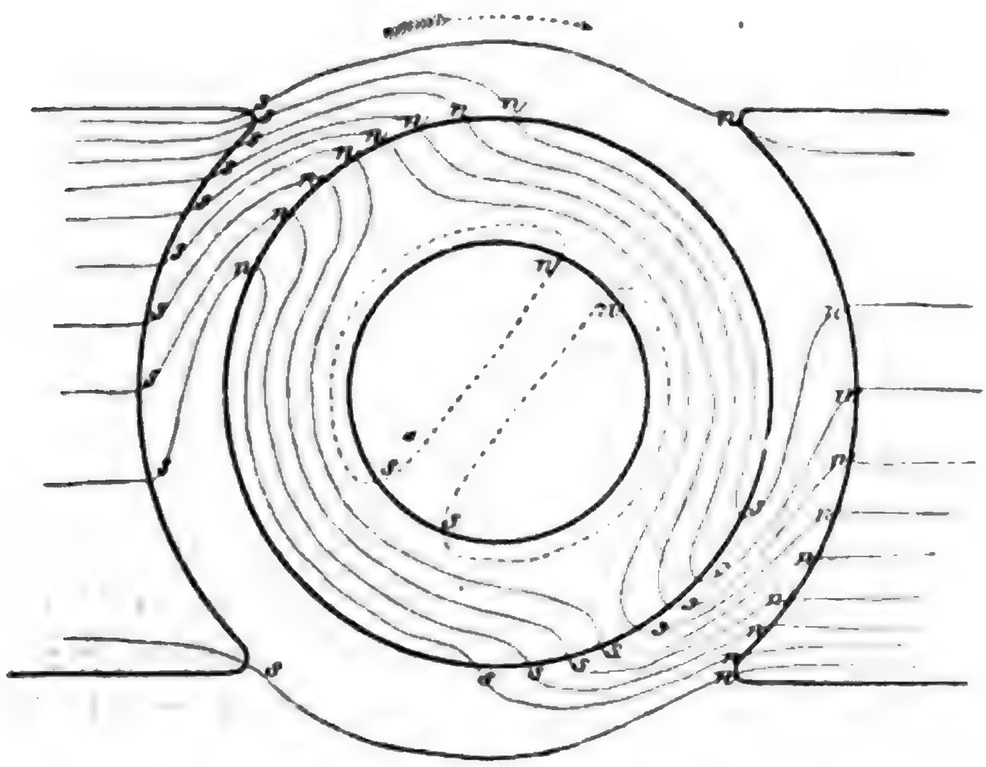


FIG. 64.—MAGNETIC REACTIONS BETWEEN FIELD-MAGNETS AND ARMATURE IN GENERATOR.

reference to Figs. 60 and 62 will also show that the magnetism of the armature reacts on the magnetism of the pole-pieces. The magnetic lines in the iron of the left pole-piece are crowded up towards the top corner, and in the right pole-

piece are crowded towards the bottom, as if the polarity had been attracted upwards on one side and downwards on the other. The density of the field is completely changed from what it was in Fig. 60. The magnetic lines at the upper left side are crowded together. The resultant N-pole of the ring—marked *n*, *n*, *n*, where the lines emerge from the ring—attracts the S-pole—marked *s*, *s*, *s*, where the lines enter the field-magnet—and the steam-engine which drives the dynamo has to do hard work in dragging the armature round against these attractions. The stronger the current in the armature coils, the stronger will be the poles in the armature, and the stronger will be the attraction of *n*, *n*, *n*, toward *s*, *s*, *s*; so the steam-engine must work still harder to keep up the speed. It will also be noticed in this figure, which relates to a ring-wound machine, that a *few* of the magnetic lines due to the current in the armature—two of them are shown dotted in the figure—leak across internally and contribute nothing to the external field. The oblique direction of this internal field marks the angle of lead of the brushes. It will be remarked that the innermost layers of iron of the ring are magnetized differently from the outermost, for the "*n*" pole of the outer layer of iron occupies a region lying obliquely on the left, while the "*n*" pole of the inner layers lies to the right of the highest point. All these phenomena—the shifting of the field—its concentration under the "leading" polar horn—its weakening under the "trailing" horn—the weak internal field—the discrepancy between the positions of the induced poles on the inner and the outer sides of the ring, can be observed in an actual dynamo. Fig. 65 shows the pattern produced experimentally in iron filings by placing a magnetized ring between the poles S N of a field-magnet, which would tend to induce in it poles n', s', and giving its own poles *n*, *s* the proper lead. It should be compared with Figs. 62 and 64.

In the case of drum-wound armatures the phenomena, though of the same kind as with ring windings, are a little less easily traced. In consequence of the over-wrapping of the windings on the outside of the armature, the currents in

some of the windings are partially neutralized in their magnetizing effect on the core by those that lie across them, and consequently the polarity due to the current is not so well marked as with ring armatures. Neither can there be any internal field. In fact drum armatures are less liable to induction troubles of all kinds than are ring armatures. But, with these exceptions, the same considerations apply to drums as to rings.

A glance at Fig. 61 will show that as the local magnetic fields due to armature currents tend to cross each of the gap-spaces twice, once in the same direction as the principal magnetic field, and once in an opposing direction, there must

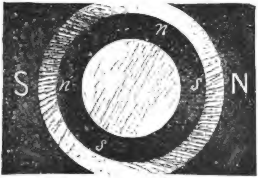


FIG. 65.—FIELD OF TWO-POLE DYNAMO.

inevitably result a weakening of the field at that part of the gap where the revolving conductors enter, and a strengthening at that part where they are leaving, exactly as though the revolving copper swept the magnetic lines round while cutting through them. From this distortion there results a similar distortion upon the curve of induction. On exploring with pilot-brush and voltmeter, one obtains curves which differ from those obtained when there is no current in the armature. Fig. 66, which shows the form of the distorted curves, should be compared with Fig. 54, p. 68.

Neutral Points.—From the earliest time that dynamos have been used, engineers have found that, in order that the

sparking may be a minimum, the brushes must be placed in certain positions, to be found by trial, called the *neutral points.* In ordinary two-pole dynamos the two neutral points lie at opposite ends of a diameter, which diameter is therefore called the *neutral line.* The term *diameter of commutation* ought to be reserved to denote the position actually occupied by the brushes, or by the coils that are passing the brushes, whether at the neutral point or not. Experience shows that in almost every case the neutral line is not mid-way between the pole-tips, but lies obliquely across, being (in a generator) shifted round a few degrees in the direction of rotation. It was early found that in many machines the exact position of the neutral point was different according to the work that the dynamo was doing. If the brushes were set so as not to spark when a certain number of lamps were alight, then, if the load of lamps was altered the machine sparked unless the brushes were adjusted to the corresponding neutral points. Hence arose the practice of mounting the brushes on *rockers* (see Plate III.), by means of which their line of contact could be altered forward or backward to the neutral point. Great attention has naturally been paid by constructors to the practical problem how to get rid of variations in the angle of lead.

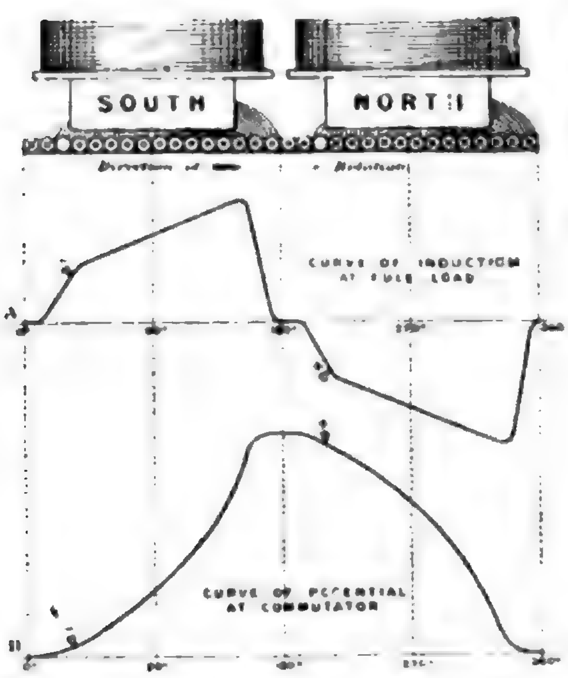


Fig. 66.

Sparking at Commutator.—Under conditions of faulty design or adjustment, and especially when a large current is flowing through the armature of dynamo or motor, bright sparks of a blue or green tint are observed at the commutator just under the tips of the brushes. The greenish hue is due to the volatilization of minute portions of copper. Severe sparking will spoil or destroy a commutator in a very

short time, and must be imperatively avoided. If a new commutator, or one that has recently had its surface renewed in the lathe, be examined after sparking has taken place, it will be noticed that the edges of many or all of the commutator segments will appear as if burned. But the burnt appearance will always be—no matter whether in generator or motor—at that edge of the segment which was the last to touch the brush; the advancing edge in the direction of the rotation will not show signs of burning. This proves that the spark that produces the damage occurs just as the copper segment, after passing under the brush, parts from contact with it. The *cause* of sparking is not difficult to show. All the conductors in the armature have their currents reversed and re-reversed at every revolution. In bipolar machines the reversal occurs twice in each revolution. In multipolar machines more than twice. In the case illustrated in Fig. 62 the current flows toward the spectator in all the conductors as they rise on the left side, but flows from the spectator in them as they descend on the right. Reversal occurs at the moment when the conductor, or the section of which it forms part, passes the brush or undergoes commutation. The production or non-production of sparks depends on the conditions under which the commutation or reversal of current takes place, and is a consequence of the property of *self-induction*—the property in virtue of which (owing to the current in a conductor setting up a magnetic field of its own in the surrounding space) it is impossible instantaneously to start, stop, or reverse a current.

Consider the standard case of a ring armature constructed in secticns, each section consisting of one or two turns of conductor. The currents will be reversed successively in the separate sections, one section at a time, as they come up to the neutral points; or rather two at a time if commutation goes on simultaneously at each of the brushes. Half the current flows up the coils on the left-hand half of the ring, and the other half of the current flows up the coils on the right-hand half. If the positive brush is at or near the top, as in Fig. 67, the current flows from left to right through the

sections X and W on the left of the brush, and from right to left through the sections T and U on the right of the brush. Now as the armature turns the bars of the commutator come successively into contact with the brush. In Fig. 67 the bars *c* and *d* have already passed the brush; *e* is just leaving it, and *f* is just beginning to pass under it. For a brief moment the brush rests on two adjacent bars *e* and *f*, and thus short-circuits the section V for an instant. The duration will

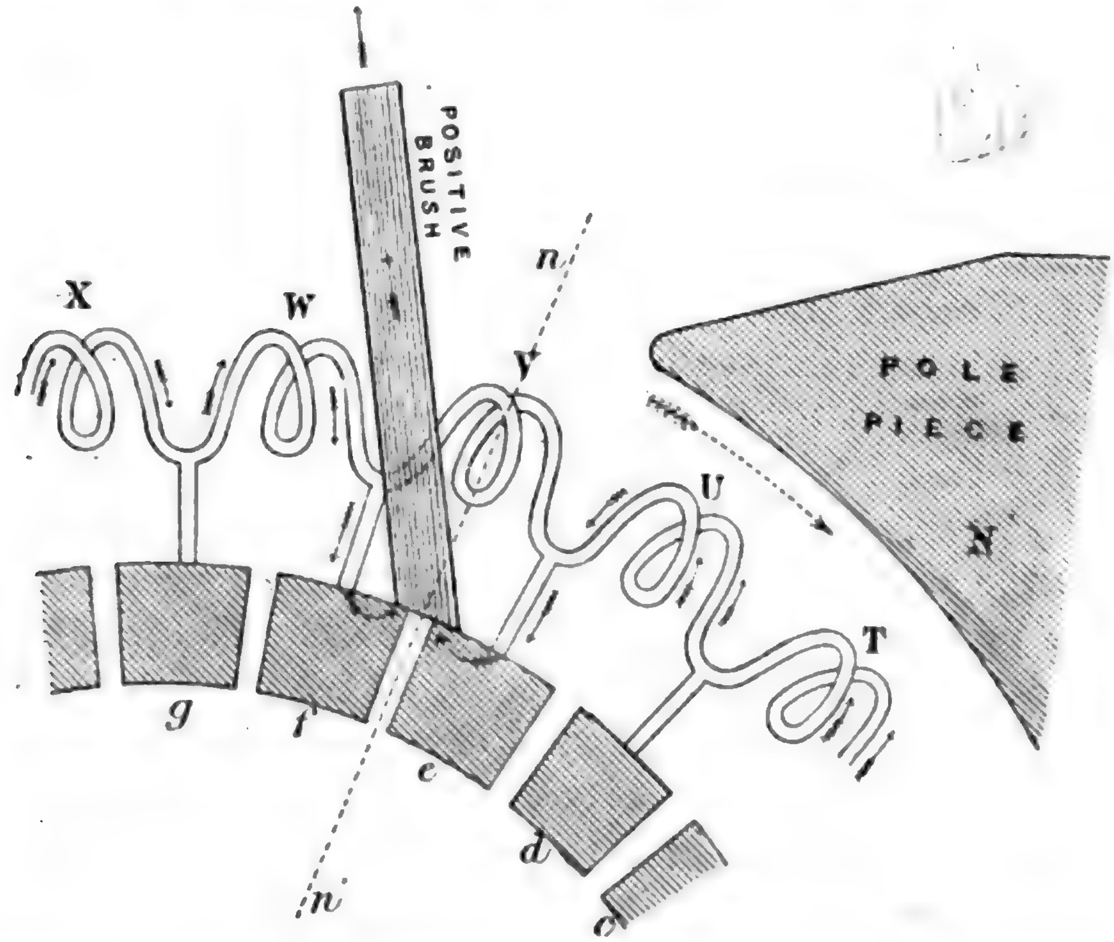


FIG. 67.—THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A GENERATOR.

obviously depend on the speed of rotation, on the breadth of the insulating gap between the commutator bars, and on the breadth of the contact surface of the brush. Now the section V a moment previously belonged to the left-hand half of the ring, and when it has passed the brush, that is to say, when *e* ceases to touch the brush, it will belong to the right-hand half of the ring. It is clear then that in the act of passing the brush the current that was flowing in the section V will be stopped, and then started again in the opposite direction

through its coils. Every section of the armature as it passes the brush will similarly be transferred from one half of the ring to the other, and will have its current reversed. This is in fact the act of commutation. Now suppose it were arranged that the act of commutation should occur exactly at the point when the coils of the section are not cutting any magnetic lines whatsoever: so that while the coil is short-circuited it shall not be the seat of any induced electromotive-force. Then the current in it will die out, and as it emerges from under the brush it will be thrown as a perfectly idle coil upon the right-hand half of the ring, in which a current is flowing toward the brush. Just before the bar *e* parts company from the brush, the current coming up through T and U is flowing through *e* to the brush: but as *e* moves away this current has suddenly to go also round the coils of V. But because of self-induction the current cannot instantly rise to its full strength in the idle coil V, hence before V really gets to work, the current sparks across between *e* and the brush. We have here supposed V to be a perfectly idle coil: now suppose that it is not idle but is actually still cutting magnetic lines, as would be the case if the brush, instead of being shifted forward to the neutral line $n\, n'$, had been given a *backward* lead further to the left. Then it is clear that during the moment of short-circuiting there will be an electromotive-force acting in the coil as it passes the brush. Such an electromotive-force, even though small, may produce momentarily a large current, because the short-circuited resistance is so small. Hence the sparking will be worse than if the coil were absolutely idle. Suppose the section of coil to have a resistance of 0·001 ohm, and to be short-circuited while moving in such a field as to generate 5 volts, the current would rise to 5000 amperes in that coil!

Now suppose that the brush is shifted just so far the other way, in the direction of the rotation,[1] that as the coil passes the

[1] In the case of a motor, which is separately considered in Chap XX., the brushes must be shifted in the *opposite* direction to the rotation; *i. e.* there must be a negative lead.

brush it is beginning to enter the fringe of the magnetic field on the right. In that case it will be beginning to cut the magnetic lines in such a way as to tend to set up a current in the reverse direction through it. The ideal arrangement is attained if the brushes be shifted just so far beyond the point of maximum electromotive-force that while the sections pass under the brush and are short-circuited they should actually have a small reverse electromotive-force induced in them; and this action should last just so long in each successive section as to stop the current that was circulating, start a current in an opposite direction, and let it grow exactly equal in strength to that which is circulating in the other half of the armature, which it is then ready to join. If this set of conditions could be attained there should be *no sparks.* A magnetic field of the proper intensity to cause reversal in the commuted section of the armature can usually be found just outside the tip of the pole-piece, for here the fringe of magnetic lines presents a density which increases very rapidly. Since a more intense field is needed to reverse large currents than is required for small ones, it follows that the angle of lead that must be given to the brushes will be slightly greater for large currents than for small ones. Time must be allowed for reversal, hence the brushes must not be so thin as merely to bridge the width of the insulation. Sparking can indeed sometimes be cured by merely using thicker brushes which prolong the time during which the section is short-circuited.

If the brushes are too thin, or are not rocked sufficiently far forward, there will be free sparking. If they are shifted beyond the neutral points, the sparking is in general less. That is to say there is usually much sparking when the lead is too little; a little sparking when the lead is too great; and no sparking when the lead is right. When the lead is greater than is necessary there is a waste of energy due to the generation in the short-circuited coil of a larger reverse current than is necessary. Moreover, as the lead is increased beyond the neutral point, all the coils that lie in the region

between the neutral point and the diameter of commutation are exerting counter electromotive-forces, and the potential at the brushes falls from its maximum.

If in any dynamo the armature current is very great, and the field-magnet very weak, it may happen that no position can be found for the brushes in which the intensity of the field is sufficient to reverse the current in the section. The greater the magnetic distortion the weaker will be the field just at that very part where a strong field is needed for sparkless reversal. Such a dynamo will spark incurably. It is evident that sparklessness will be promoted (1) by dividing up the armature into many sections, so that the reversals of the currents may be done in detail; (2) by making the field-magnet a relatively powerful one; (3) by so shaping the pole surfaces as to give a suitable fringe of magnetic field of sufficient intensity; (4) by choosing brushes of suitable thickness, and keeping their contact surfaces well trimmed. (See also Chapter XVI. on Dynamo Design.)

Beside the cause of ordinary sparking explained above there are some causes of an exceptional nature. In those dynamos (chiefly those used in arc lighting) that are constructed to work at high potentials approaching or exceeding 1000 volts, there sometimes occurs a phenomenon known as "flashing-over." A long blue spark will on a sudden alteration of the resistance of the circuit be drawn out around the circumference of the commutator from brush to brush. This spark, which is more of the nature of an arc, does little harm in the case of those dynamos which are constructed with commutators of few parts separated by air-gaps, but is very harmful in the case of dynamos having commutators of the ordinary sort, with thin mica insulation between the bars; for these are easily short-circuited by the flash-over.

Another cause of sparking is want of symmetry in the winding of the armature. If one of the sections is short-circuited by any accident, or has become disconnected from its neighbour, sparking will result at that part of the commutator. Jumping of the brushes when the collector is

G 2

untrue, or when the brush-holders are defective, is another prolific cause of sparking.

Formerly the fact that a lead must be given to the brushes was ascribed to a sluggishness in the demagnetization of the iron of the armature, but this view is apocryphal. Indeed, the reverse is probably true; and, until further experimental evidence is forthcoming, it will be assumed that the alleged magnetic lag is negligibly small in its effects. For further discussion of this, see some experiments which were described

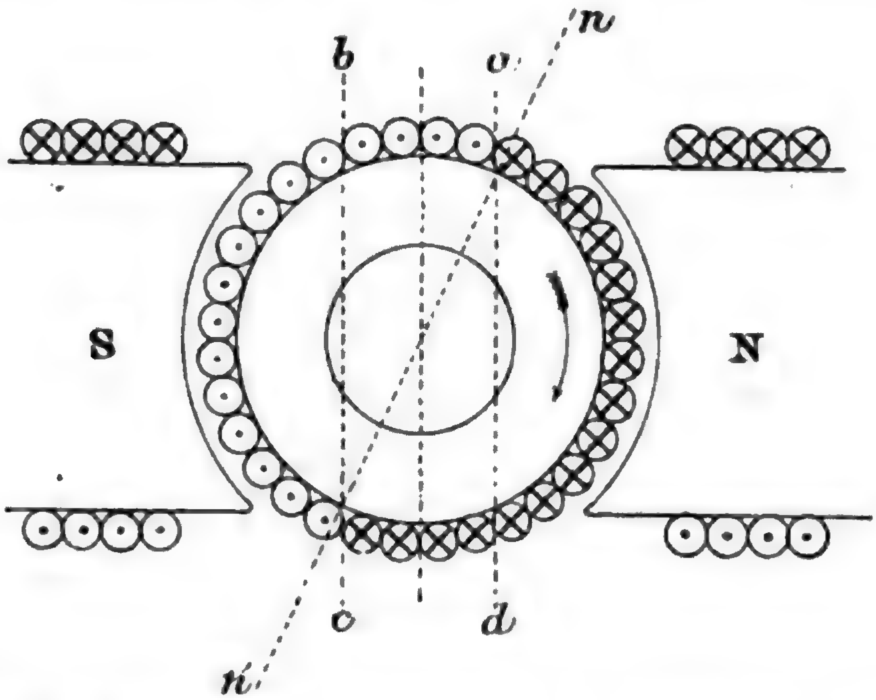


FIG. 68.—DEMAGNETIZING ACTION OF ARMATURE CURRENT OF GENERATOR.

in Appendix V. of the third edition of this work. The generation of eddy currents in any part of the revolving armature will necessarily be accompanied by a demagnetizing action, and will also affect the lead.

Demagnetizing Action of Armature.—If in a dynamo there is a forward lead given to the brushes for the purpose of stopping the sparking, there at once results another reaction, namely, the production of an actual demagnetizing tendency or "back magnetomotive-force." That the armature current does so act is readily demonstrated by considering Fig. 68. Here the field-magnet and armature are represented as before, but the brushes have been given a

forward or positive lead; the neutral line $n\,n'$ lying obliquely. The currents are flowing toward the observer in the armature conductors on the left of the neutral line, and from the observer in those on the right of that line. Now let the two lines $a\,b$ and $c\,d$ be drawn squarely across the armature through the points of commutation corresponding to the two brushes. These lines intersect the outline of the armature in four points. In the diagram there are thirty-two conductors spaced out around the core disk of the armature; and as this armature is drum-wound, the end connexions of the

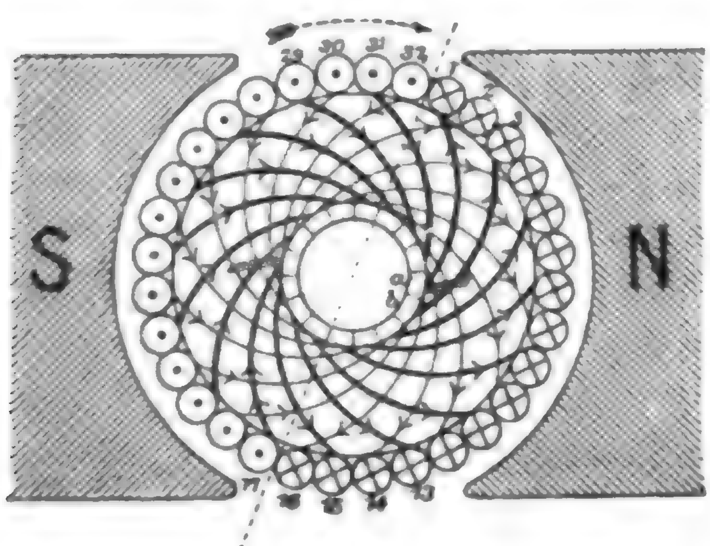


Fig. 69.
Actual Connexions at End of Drum-windings.

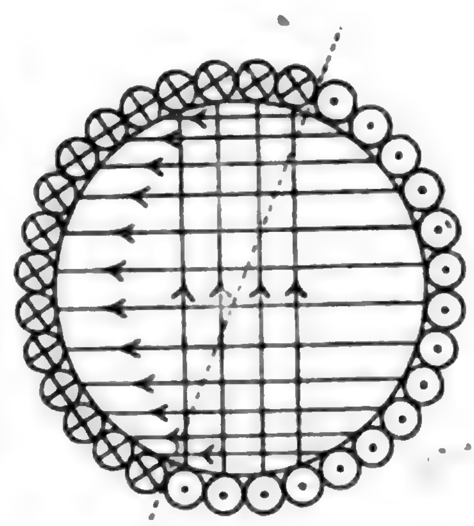


Fig. 70.—Conductors Grouped into Cross Magnetizing and Demagnetizing Belts.

conductors will probably be somewhat like those shown in Fig. 69, where each conductor is connected across the end by a double-curved connector to the conductor that is next to the one diametrically opposite.[1] Now so far as any magnetizing actions are concerned it does not matter what the end connexions are, provided they are compatible with the flow of current indicated above in Fig. 68, with current advancing along the sixteen conductors on the left of $n\,n'$, and retreating along the sixteen on the right of $n\,n'$. Hence we may consider them, temporarily, as grouped in any way that will assist us to understand their action. Suppose,

[1] For modes of connecting drum-windings, see Chapter XIII.

then, that the four conductors from 29 to 32 are joined across the ends[1] to the four from 13 to 16 (Fig. 70); and let the twelve conductors from 1 to 12 be joined across to the twelve from 17 to 28. Our armature windings are now distributed into two belts, one horizontal belt of twelve windings which tends simply to *cross-magnetize*, and one vertical belt of four windings which tends simply to *demagnetize;* for it will be seen that the direction of the circulation around the vertical belt is opposite to the direction of the circulation of current in the magnetizing windings. The breadth of the belt of demagnetizing windings is obviously proportional to the angle of lead, since it subtends double that angle. If the armature in question were carrying 100 amperes then, since there are two paths through the armature circuit (pp. 62 and 71) each conductor must carry 50 amperes. Hence the number of cross-magnetizing ampere-turns is $50 \times 12 = 600$; and the number of demagnetizing ampere-turns is $50 \times 4 = 200$.

Now the cross-magnetizing action which, as we have seen, distorts the field, does of itself slightly diminish the flux of magnetic lines that crosses the armature core from side to side, because in the oblique resultant direction of the magnetization the increased flux tends to produce greater saturation in the pole corners. For other researches on the effect of a cross magnetism in diminishing the magnetism of the core, see papers by Siemens[2] and Schültze[3] in *Wiedemann's Annalen.* Schültze, in the course of twenty-four experiments, found that the cross-magnetization of an iron core always diminished the longitudinal magnetization. More recent experiments on these effects are those of Frölich, Kennelly,[4] and Stromberg.[5]

In a Manchester dynamo, tested by Prof. Ayrton,[6] 5846

[1] See Swinburne in *Journal Inst. Elec. Engineers*, xv. 542, 1886.

[2] Werner Siemens. *Wiedemann's Annalen*, xiv. p. 634, 1882.

[3] Schültze. *Wied. Ann.*, xxiv. p. 663, 1885. See also Oberbeck, Habilitations-Schrift, 1878.

[4] *Electrician*, xxv. 111, 1890.

[5] *Centralblatt für Elektrotechnik*, 1887, p. 283.

[6] *Journal Inst. Electrical Engineers*, xix. 175, 1890.

ampere-turns of excitation were needed when no lamps were on, and 10,000 when the machine was furnishing its full output of current: of the additional 4154 ampere-turns, 1754 were needed to compensate for the lost volts (due to internal resistance and lessened permeability) and 2400 to compensate for the demagnetizing effect of the armature current with the increased lead needed to prevent sparking. The greater the lead given to the brushes in a dynamo used as a generator, the greater is the demagnetizing effect of the armature current. In motors the direction of the armature current is opposite to that in the dynamo (that is to say is *against* the electromotive-force), a negative or backward lead has to be given to the brush to avoid sparking—and this backward lead also results in a demagnetizing tendency. If a negative lead (*i.e.* a displacement from the neutral line in the opposite direction to the sense of the rotation) is given to the brushes of a generator, the magnetizing effect of the armature currents will tend to assist the magnetization of the core. Drs. J. and E. Hopkinson [1] have shown that if a backward lead is given, a generator can excite itself by means of the armature currents only; but in such case of negative lead there was a destructive amount of sparking. The demagnetizing effect is of course proportional to the number of effective ampere-turns of the armature circuit that surround the magnetic circuit, and therefore to the actual number of ampere-turns included, as we have seen, in a belt of double the angular breadth of the angle of lead.[2] According to Kapp a smaller actual number of compensating turns is required in practice. Several expedients have been proposed to compensate the cross-magnetizing tendency of the armature currents, and so obviate the variations of lead. In one due to Mather,[3] a small bar electromagnet excited by the armature current is placed perpendicularly between the pole-pieces.

[1] *Phil. Trans.*, 1886, part i. p. 347.

[2] According to Peukert, who, however, does not specify the angle of lead, the demagnetizing effect of the armature current is proportional to the 1·3 power of the armature current. See *Centralblatt für Elektrotechnik*, ix. 484, 1887.

[3] See *La Lumière Électrique*, xix. 404, 1885.

Swinburne[1] has discussed the advantages of various similar arrangements for this purpose. Professor E. Thomson proposes to place a series coil on a movable frame over the armature and tilt it till it brings back the neutral point. These devices, together with the recent proposals of Ryan and of Sayers, are considered in Chapter XVI. on Dynamo Design.

The interference of the armature with the magnetization of field-magnets may also be studied in relation to the "characteristic" curves of dynamo machines (see Chap. X.), which are used to show the rise of the electromotive-force of the machine in relation to the corresponding strength of the current; this rise being proportional to the magnetization through the armature. Now the characteristics of nearly all series-wound dynamos show a decided tendency to turn down after attaining a maximum; and in some machines, for example the older form of Brush arc-light dynamo with cast-iron ring, this reaction is very marked. The electromotive-force diminishes, though the magnetizing force of the field-magnet coils goes on increasing. The effect is due partly to the distortion of the magnetism, but mostly to the demagnetizing effect as the lead of the brushes is increased. It is at least significant that in the older form of Brush machine, where the reduction of electromotive-force is very great, there is also such a mass of iron in the armature, and so variable a lead at the brushes.

The questions of lead of brushes, sparking, and field necessary to reverse the current in a section is further considered in Chapter XVI. in relation to the design of dynamos and the load (or ampere-turns) which an armature can carry.

Dead Turns.—Owing to the various reactions that depend upon the speed, it is found that the electromotive-force of a machine excited by a given current is not rigidly proportional to speed, but falls off somewhat at higher speeds. The machine acts as though some of its revolutions were not

[1] *Journal Inst. Electrical Engineers*, xix. 105, 1890.

effective. The name *dead-turns* is given to the number of revolutions by which the actual speed at any output exceeds the number that would be needed for strict proportionality.

Spurious Resistance.—There is yet another effect which results from the existence of self-induction in the coils of the armature. In each section the current tends to go on, and in fact does actually go on for a brief time after the brush has been reached. Then the energy of the current in that section is wasted in heating the copper wire during the interval when it is short-circuited; and as it passes on, energy must again be spent in starting a current in it in the inverse direction. All these reactions are of course detrimental to the output of current by the dynamo: especially the loss in short-circuiting. It has been shown by M. Joubert[1] that the loss of energy due to the reversals of the current in the sections of a ring armature is equal to $n\,L\,C^2/4$ per second, where n is the number of revolutions per second, L the coefficient of self-induction for the entire ring, and C the armature current. Professors Ayrton and Perry very aptly pointed out[2] that the matter may be conveniently expressed in another way. Since the energy per second conveyed by a current running through a resistance r is equal to $r\,C^2$, it is evident that the energy lost per second by self-induction is the same as if there were an additional resistance in the armature of the value $r = n\,L/4$. There is, therefore, in a rotating armature, an *apparent* increase of resistance proportional to the speed, and this apparent increase, due to self-induction, cannot be got rid of by subdividing the armature into a larger number of sections. It can be diminished by using more iron in the magnetic circuit, and fewer turns of wire in the armature. The value here assigned depends on the assumption that during the moment of short-circuiting the current in the section simply dies out. If it is stopped and reversed by the introduction of a counter electromotive-force, as it ought to be, the value will be less.

[1] *Comptes Rendus*, June 23, 1880, January 9, 1882, March 5, 1883; and *L'Électricien*, April 1883.

[2] *Journ. Soc. Teleg. Eng. and Electr.*, xii. No. 49, 1883.

The existence of an apparent resistance varying with the speed was first pointed out by M. Cabanellas.[1]

Eddy-Currents.—There are two other inductive reactions in the armature to be considered. If any of the framework or metal supports that carry the armature constitute closed circuits which can cut the magnetic lines, they will be the seat of wasteful parasitic currents, which will eddy round in them, heating them and absorbing power. In the iron of the armature cores, if not properly laminated, internal *eddy-currents* (the so-called "Foucault currents") may be set up, absorbing energy and producing detrimental heat; and such currents will also be produced within the conductors which form the coil of the armature, if these are massive as in the "bar-armatures" used for machines that have a large output of current. Frölich, in 1880,[2] pointed out the effect of the presence of these currents; and to them he attributed not only the otherwise unexplained deficit in the work transmitted electrically by a generator to a motor, but also the diminution in the effective magnetism (mentioned above as a result of cross-magnetism, and found by Frölich to amount to 25 per cent. of the whole) observed with great currents and high speeds; and further he attributed to this cause the apparent increase in the number of "dead-turns" at high speeds. Doubtless such currents exist, and the energy they waste will be nearly proportional to the square of the speed:[3] but they may be indefinitely diminished by proper lamination, insulation, and disposition of the structures of the armature.

Lamination.—The rules for the proper lamination of structure are different in the different parts; for in the armature core it is desired to cut off all circulation of current that

[1] *Comptes Rendus*, January 9, 1882, and Nov. 24, 1884; see also Picou, *Manuel d'Électrométrie*, p. 123; and Lodge in *Electrician*, July 31, 1885.

[2] Berlin Academy, *Berichte*, Nov. 18, 1880; and *Elektrotechnische Zeitschrift*, i. 174, May 1881; also ix. Nov. and Dec, 1888.

[3] Clausius has introduced into his equations (*Wied. Ann.*, xx. 354, 1883; and *Phil. Mag.*, series 5, xvii. 46 and 119, 1883) terms to include the effects of the eddy-currents. They have also been theoretically treated by H. Lorberg (*Wied. Ann.*, xx. 389, 1887).

might be induced parallel to the armature conductors; and in the armature conductors it is desired to cut off all flow of current from one side or edge of the conductor to the other. The planes of lamination must of course be arranged to cut right across the direction in which the parasitic current might otherwise flow. Now since (see p. 23) the direction of the induced electromotive-force, the direction of the motion, and the direction of the magnetic lines are all three at right angles to one another, it suffices in each case to describe the plane of lamination, by stating to which of these three directions it must be normal. It will then contain, or be parallel to, the other two directions.

Direction of	Direction of Lamination Planes.		
	In Armature Cores.	In Armature Conductors.	In Polar Masses.
Motion	parallel	normal	parallel
Magnetic Lines	parallel	parallel	parallel
Induced Electromotive-force ..	normal	parallel	normal

It will be noticed that the lamination for the polar masses is the same as for the core; so that the polar masses are virtually continuations of the core-disks.

The necessity for dividing the cores of drum armatures and of ring armatures (if cylindrical, not discoidal) into core-disks, may be illustrated as follows:—In any conductor rising in the left-hand gap-space there will be generated an electromotive-force tending from back to front. Hence if the core were of solid iron, a current would flow forwards along the outer part of the core on the left, and back along the outer surface on the right. Division of the core into disks will obviously minimize such currents. It will not, however, entirely eliminate them, for as Fig. 71 shows in the sectional view of the core-disks, it is possible for eddy-currents to flow in the substance of these. As a matter of fact it is found that if they are too thick, or are not properly insulated from one another, they heat: and the heating is

mainly at the outer surface, where the eddies are strongest. As a general rule it may be said that core-disks should not exceed 2 millimetres in thickness. The same thickness is suitable for the ribbon cores of discoidal rings. The new laminated armature of the Brush arc-light machine, when used in place of the old solid armature, was found to diminish greatly the number of "dead turns," besides saving much energy previously lost in heating. If there is a stray magnetic field leaking from the flanks of the polar masses into the flat surface of the end-disks of the core, eddy-currents will

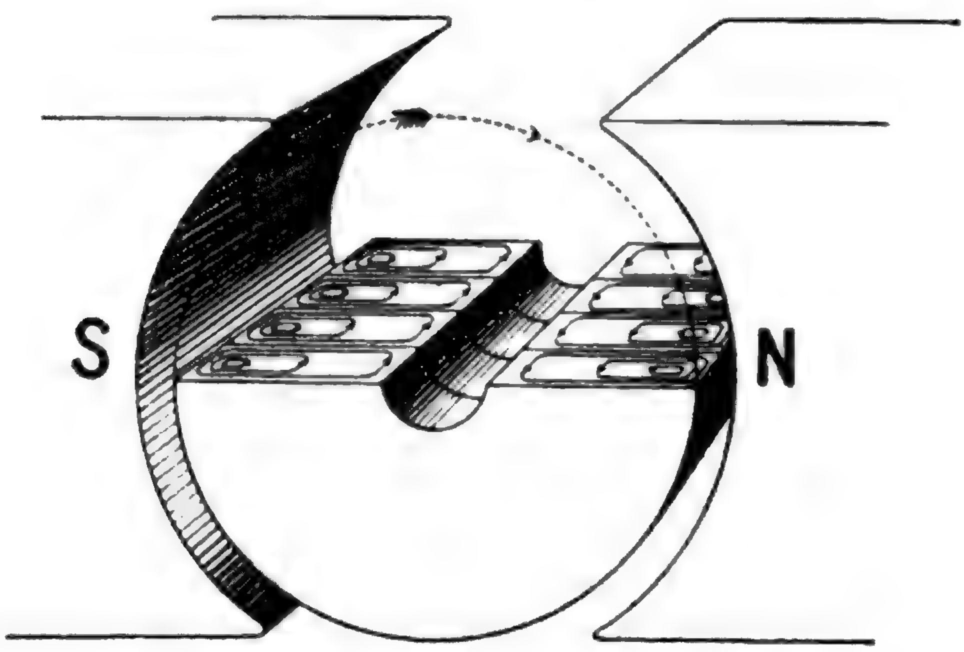


FIG. 71.--EDDY-CURRENTS IN CORE DISKS.

also be set up in the latter. This can be obviated by making the length of the armature core rather greater than the length of the polar masses parallel to the axis.

With ring armatures that have an internal field (see p. 71) similar eddies will be set up in the driving spindle and in the metal arms that support the core, wasting power and heating them.

Eddy-currents in Pole-pieces.—If the masses of iron in the armature are so disposed that as it rotates, the distribution of the lines of force in the narrow field between the armature and the pole-piece is being continually altered, then, even though the total amount of magnetism of the field-magnet remains unchanged, eddy-currents will be set up in the pole-

piece and will heat it. This is shown by Figs. 72 to 77, which represent the effect of a projecting tooth, such as that of a Pacinotti ring, in changing the distribution of the magnetism of the pole-piece. Figs. 75 and 76 (corresponding respectively to Figs. 73 and 74) show the eddy-currents, grouped in pairs

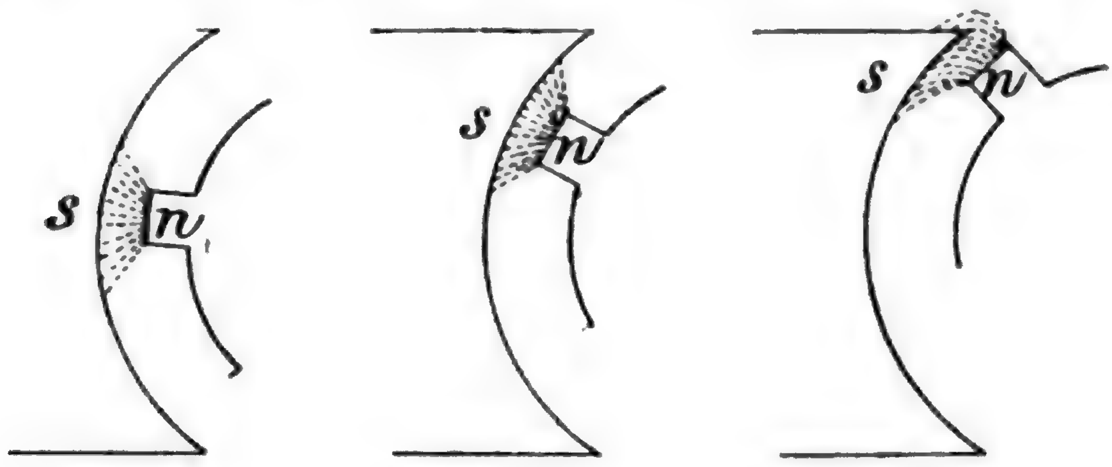


FIG. 72. FIG. 73. FIG. 74.
ALTERATION OF MAGNETIC FIELD DUE TO MOVEMENT OF MASS OF IRON IN ARMATURE.

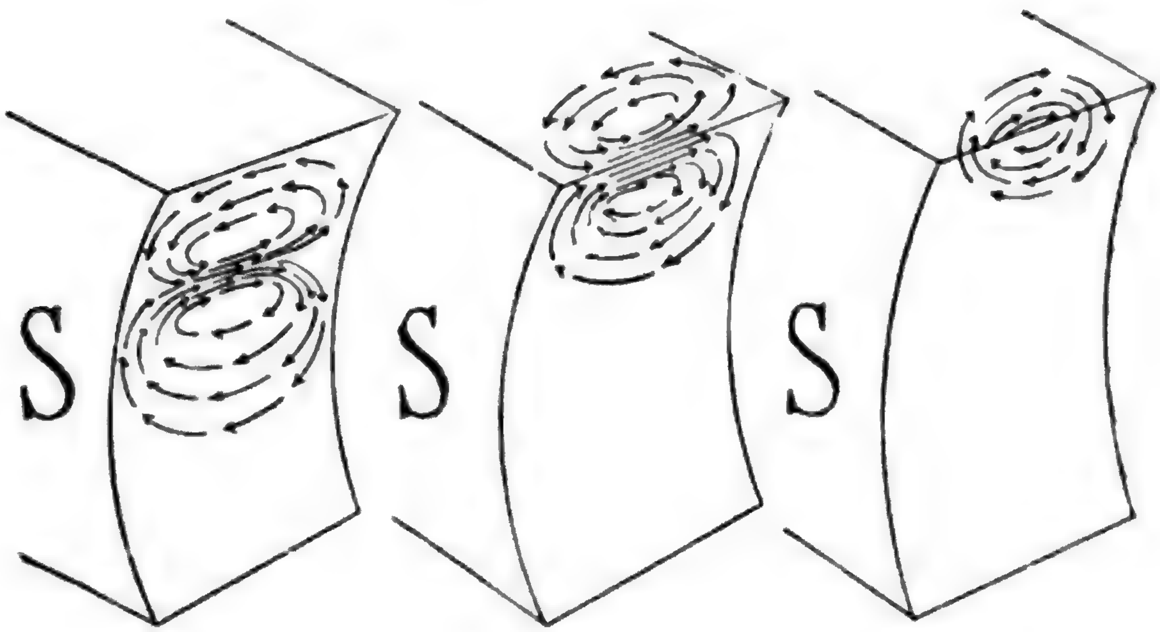


FIG. 75. FIG. 76. FIG. 77.
EDDY-CURRENTS INDUCED IN POLE-PIECES BY MOVEMENT OF MASSES OF IRON.

of vortices. The strongest current flows between the vortices, and is situated just below the projecting tooth, where the magnetism is most intense; it moves onward following the tooth. Fig. 77 shows what occurs during the final retreat of the tooth from the pole-piece. These eddy-currents penetrate

into the interior of the iron, although to no great depth. Clearly the greatest amount of such eddy-currents will be generated at that part of the pole-piece where the magnetic perturbations are greatest and most sudden. A glance at Figs. 62, 65, 76 and 77 will at once tell us that this should be at the "leading" corner or "horn" of the pole-piece of the generating dynamo. As a matter of fact, when any dynamo which has horned pole-pieces (such as the Gramme) has been running for some time as a generator this is found to be the case. The "leading" horns *a* and *c* (i. e. those which point in the direction of the rotation) are found to be hot, whilst the "trailing" horns are found to be comparatively cool. When the dynamo is used as a motor, the reverse is found to be the case: the "leading" horns are cool, the "trailing" horns are hot. A reference to the magnetic field of the motor, as described in Chap. XX., will explain the latter case. Closely connected with this effect is another, first pointed out to the author by M. Cabanellas. A Gramme magneto-machine with permanent magnets is observed to lose power during its use as a motor; the field-magnets decrease in strength. If, then, it is used as a generator, the field-magnets retain their magnetism. The effect is explicable[1] when the magnetizing effect of the eddy-currents is taken into consideration.

Remedy for Induction Troubles.—The one important way of diminishing these deleterious reactions is happily a very simple one. It is clear that the demagnetizing effect is due to the lead of the brushes, and this again is due to the cross-magnetizing action. This therefore must be compensated or reduced to a minimum by some means. It has been shown that the electromotive-force of the dynamo is proportional to three things, the number n of revolutions per second, the total number N of magnetic lines in the effective field, and the number Z of conductors around the armature. Now, for a given size of armature, the inductive reactions are proportional to Z. If we can decrease Z while increasing either of the other terms, we may thereby decrease the deleterious

[1] See remarks by the author at the International Conference of Electricians at Philadelphia, 1884 (reported in *Electrical Review*, Dec. 13, 1884).

reactions and yet keep the same electromotive-force as before. Now, it is inconvenient for mechanical reasons to increase the speed. The only way then is to increase N, the magnetic flux. This can be done by having relatively big field-magnets. If the field-magnets are large and of wrought iron, and if there is a sufficiently large cross-section of iron in the armature core, then, without increasing the speed, we may get the same electromotive-force while using fewer turns of wire on the armature. The ideal dynamo for constant pressure work has but one turn of wire to each section. It will have practically no lead at the brushes, will not spark, and its internal resistance will be practically *nil*.

It is also important to observe that distortion of the magnetic field and some of the resulting troubles can be partially obviated by so shaping the polar surfaces that they come nearer to the armature at the region at right angles to the diameter of commutation; the pole-pieces being cut away so as to give a wider clearance at the outer edges. It is obviously possible by proper shaping to produce concentration of the magnetic lines at any desired region of the magnetic field. Ryan[1] has made a special study of the relation between the polar shape, the breadth of the gap-space, and the resulting curve of induced electromotive-force. These matters also are discussed in Chapter XVI. under the heading of Dynamo Design.

[1] *Amer. Inst. Electrical Engineers*, Sept. 22, 1891.

CHAPTER V.

MECHANICAL ACTIONS AND REACTIONS IN THE ARMATURE.

Drag on Armature Conductors.—Whenever a conductor carrying an electric current lies in a magnetic field across the magnetic lines, it experiences a mechanical force. This force always tends to drag the conductor sideways out of the field, and acts in a direction at right angles to the magnetic lines and at right angles to the conductor itself. Rules for remembering the relation between the directions of the magnetic lines, the current, and the resulting force, have been given by various writers. The most convenient rule is that of Fleming, in which the three directions are represented respectively by the fore-finger, the middle-finger, and the thumb of the *left* hand.[1] Except in those cases where the conductors are embedded in slots or holes in the iron core-disks, the drag comes on the conductor itself. In a motor it is this drag on the conductors which drives the armature. In a dynamo the drag acts against the driving power of the steam-engine and opposes the rotation. When a mechanical engineer first considers a dynamo he is often puzzled to understand what there is in it that necessitates so much driving power. He sees the armature revolving with ample clearance between the polar faces of the field-magnet. The friction of the bearings

[1] Contrast with p. 23, where, for the current generated in a *dynamo* the *right* hand is used. Remember that in a dynamo the direction of the current agrees with that of the induced electromotive-force, whereas in a motor the current flows against the induced electromotive-force. Further, in the dynamo the mechanical drag acts against the direction of motion, whereas in a motor the drag produces the motion in the same direction as itself. Hence the use of *right* hand for dynamo, *left* hand for motor, to give the relation between magnetism, current and motion.

does not absorb more than a minute fraction of the horse-power delivered by the engine. He sees the brushes pressing against the commutator, but knows that their friction is also a negligible quantity; moreover, he is soon informed that friction has nothing to do with the operation of the machine. Where does the power go to? What is it that requires such a force to be continually exerted to keep up the rotation? The answer is, that there is a continual drag of the invisible magnetic lines on the conductors through which the current is flowing: that the generation of the current depends on the conductors being forced across the field that drags at it. In every form of apparatus generating currents by magneto-electric induction, the currents generated produce a mechanical reaction tending to stop the very motion that generates them.

The drag of a magnetic field upon a conductor that carries a current may be considered from the magnetic point of view.

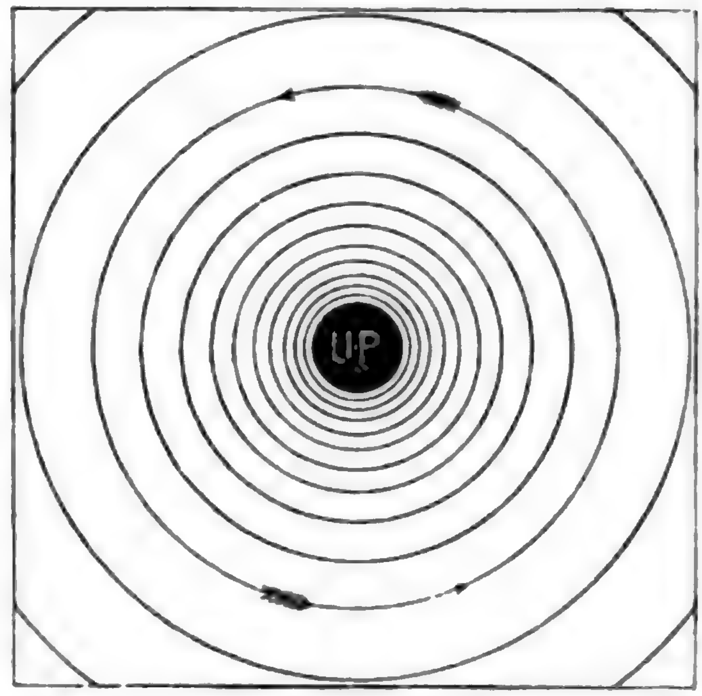


FIG. 78.—MAGNETIC FIELD OF A STRAIGHT CONDUCTOR CARRYING A CURRENT.

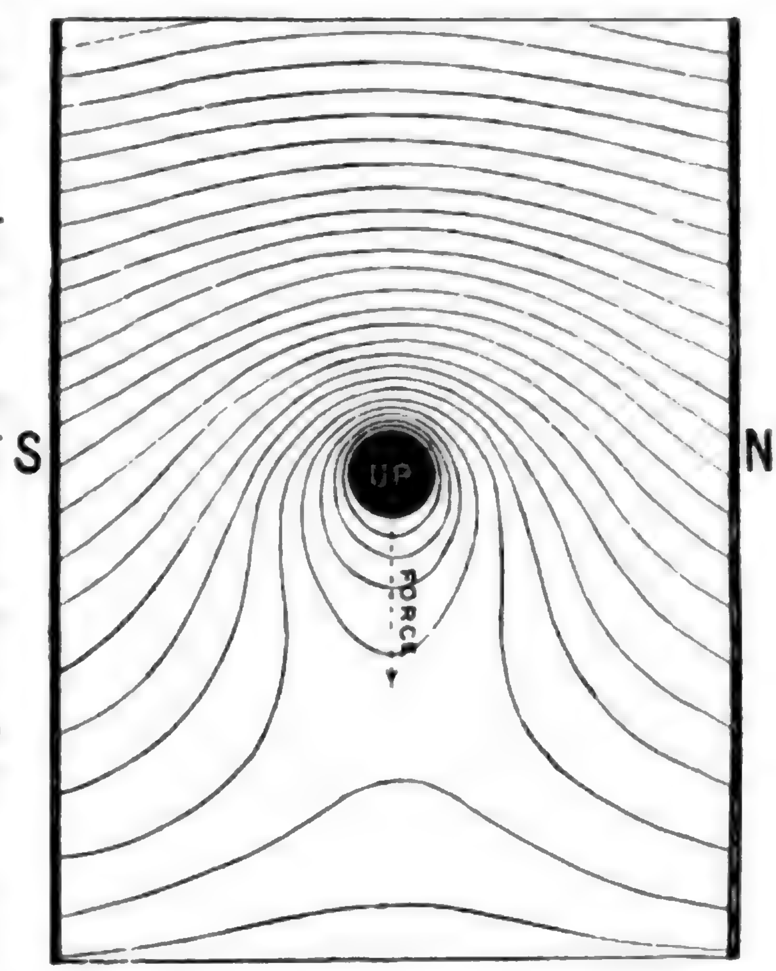


FIG. 79.—MAGNETIC LINES DUE TO CONDUCTOR CARRYING CURRENT PLACED IN MAGNETIC FIELD.

As pointed out on p. 27, above, such a conductor is surrounded by a whirl of magnetic lines. Around a long straight conducting wire not placed in any magnetic field, these magnetic lines form a system of concentric circles (see Fig. 13, p. 27) which are close together near the conductor, and wider apart at a distance away, resembling Fig. 78 in general disposition.

If the current is coming towards the observer, or *up*, in the figure which shows a cross-section of the conductor, the positive direction along the magnetic lines will be counter-clock-wise. If now such a conductor be placed in a uniform magnetic field—one, for example, between a large north magnetic pole on the right and a south magnetic pole on the left, a compound field will be produced, due to the blending of the magnetic lines of the current with those of the field. In considering this distorted magnetic field it should be remembered that the mechanical actions that result may always be known by supposing the magnetic lines to act as elastic cords tending to shorten themselves. There is in fact a tension along the magnetic lines and a pressure at right angles to them, both proportional at every point to the

FIG. 80.—ACTUAL MAGNETIC FIELD AROUND CONDUCTING WIRE IN MAGNETIC GAP.

square of their density. A mere inspection of the lines of Fig. 79 will accordingly show that there will be a resultant drag upon the conductor in the direction shown by the dotted arrow.

The actual magnetic field produced around a conducting wire in a gap between two poles, as revealed by iron filings, is shown in Fig. 80. We may consider this as approximately representing that which goes on in a dynamo, or in a motor, in each of the gap-spaces between the armature core and the adjacent polar face. Each conductor in the gap will be similarly dragged by a force proportional to the intensity of the magnetic field and to the strength of the current.

Effect of Embedding Armature Conductors. — If the conductors are embedded in slots or holes in the core-disks (see Figs. 213 to 217) the drag then comes not upon the copper conductors, but upon the iron; the magnetic field between the core-disk and the pole-faces being distorted by the current in the embedded conductors. In fact the conductor no longer lies in a strong magnetic field; the magnetic lines being carried past it on either side, very few going through it. Fig. 81 may assist the understanding of this point. It seems paradoxical that though the conductor so embedded is protected from mechanical drag, and from eddy-currents, owing to its not being in the field, nevertheless in its revolution it still cuts all the magnetic lines precisely as if it were not protected. The effect is as though the magnetic lines flashed across the slots from tooth to tooth, instead of passing across the intermediate slot at the ordinary angular velocity. In addition to the advantages already mentioned as possessed by these forms of construction they have also the very important one of reducing the breadth of the magnetic gap to a mere clearance.

FIG. 81.—MAGNETIC FIELD OF SLOTTED ARMATURE.

Torque and Speed.—Engineers recognize that power, being the rate of doing work, can always be expressed as the product of two factors. In the case of rectilinear motion, the power may be expressed as the product of force and speed. For example, if the force pulling along a belt[1] be equal to the weight of 66 lbs., and the belt-speed be 2000 feet per minute, the amount of power it is delivering is 132,000 foot-pounds per minute, or 4 horse-power.

But the power may be equally well expressed in terms of angular force (*i.e.* torque) and angular speed; and these quantities are more convenient in the case of power transmitted along a rotating shaft.

The useful term *torque*, now generally accepted by engineers, was originally suggested by the late Professor James Thomson. It is the same thing as that which has gone by the names of "turning moment," "moment of couple," "axial couple," "angular force," "axial force," in German by that of "Zugkraft," and in French by those of "effort statique," and "couple mécanique." *Torque* is preferable in many ways to any of the older terms. Just as the Newtonian definition of *force* is that which produces or tends to produce motion (along a line), so *torque* may be defined as that which produces or tends to produce *torsion* (around an axis). It is better to use a term which treats this action as a single definite entity than to use terms like "couple" and "moment," which suggest more complex ideas. The single notion of a twist applied to turn a shaft is better than the more complex notion of applying a linear force (or a pair of forces) with a certain leverage.

For torque we shall use the symbol T. If force f acts with leverage (*i. e.* radius) r, the torque is equal to $f \times r$. If the force is in pounds' weight and radius in feet, the torque will be expressed in pound-feet; *i. e.* in terms of the number of pounds which, acting with a leverage of one foot, would produce an equal tendency to turn. If force is given in dynes and radius in centimetres, the torque will be expressed in dyne-centimetres.

[1] Or more precisely, the difference between the forces in the tight and slack parts.

In order to bring—

dyne-centimetres	to	gramme-centimetres,	divide by 981
dyne-centimetres	to	metre-kilogrammes,	divide by 981×10^5
dyne-centimetres	to	pound-feet,	divide by $13{\cdot}56 \times 10^6$
pound-feet	to	metre-kilogrammes,	divide by 7·23

Angular speed is commonly expressed by engineers in terms of the number of revolutions per minute, or, sometimes, of revolutions per second. The scientific mode is to express it in *radians per second.* (The radian is that angle whose arc equals the radius; so that 2π radians equal one revolution or 360°.) The symbol for angular speed is ω, so that if n represents the revolutions per second, $\omega = 2\pi n$.

In order to bring:—

revolutions per minute	to	revolutions per second,	divide by 60
revolutions per second	to	radians per second,	multiply by 2π
revolutions per minute	to	radians per second,	divide by 9·55
radians per second	to	revolutions per minute	multiply by 9·55

We have then the following relations between linear force f, linear speed v, torque T, angular velocity ω, radius r, revolutions per second n, and power w.

$$w = v \,.\, f = \frac{v}{r} \,.\, f r = \omega \mathrm{T} = 2 \pi n \mathrm{T}.$$

The power w will be expressed in *ergs per second*, if v is given in centimetres per second and f in dynes; or if T is given in dyne-centimetres. If T is in pound-feet, w will be expressed in foot-pounds per second.

In order to bring:—.

ergs per second	to	watts,	divide by 10^7
ergs per second	to	kilogramme-metres per second,	divide by $9{\cdot}81 \times 10^7$
ergs per second	to	foot-pounds per second,	divide by $1{\cdot}356 \times 10^7$
ergs per second	to	horse-power,	divide by 746×10^7
watts	to	horse-power,	divide by 746
watts	to	chevaux-vapeur,	divide by 736
watts	to	foot-pounds per second,	divide by 1·356
watts	to	kilowatts,	divide by 1000
kilowatts	to	horse-power,	multiply by 1·345

Output of Dynamos and Motors.—A good dynamo will convert over 90 per cent. of the mechanical power supplied to it into electric power. Similarly a good motor will convert over 90 per cent. of the electric power supplied to it into mechanical power. Both mechanical power and electric power may be expressed in terms of the same units, either in *horse-power*, or in *watts*, or in *kilowatts*.

Approximate calculations of the horse-power required for a dynamo of any prescribed output are readily made. Multiplying the number of amperes C of current which the dynamo is to yield, by the number of volts e of pressure at which the current is supplied, gives the output in *watts*. Dividing by 746 gives the corresponding electric horse-power, which will be about 90 per cent. of the mechanical horse-power to be supplied to the shaft of the dynamo.

Example: A dynamo is required to furnish 300 amperes (to light 600 glow lamps) at a pressure of 105 volts. Output is 31,500 watts = 42·2 horse-power (electrical). Therefore allow 46·9, or say 50 (mechanical) horse-power.

In the converse way we may calculate the requisite supply of electric power to a motor.

Example: A motor is required to give an actual output of 5 horse-power. Multiplying by 746, we find it must give out 3730 watts as mechanical power; which will be about 90 per cent. of the electrical power supplied to it This will therefore need to be about 4144 watts. If the supply is from mains that are at a pressure of 200 volts, the current required will consequently be a little over 21 amperes.

Relation between Torque and Current.—Since the electric power given out by the armature of a dynamo is the product of two factors—volts and amperes—and the mechanical power supplied to it by the rotating shaft is also the product of two factors—speed and torque—it becomes a matter of some interest to ascertain whether there is any direct relation between the factors themselves. Let E stand for the volts generated in the armature, and C_a for the amperes flowing

through it. We may then equate the two separate expressions for the number of watts of power supplied to and furnished by that armature as follows:—

$$\text{watts} = E\, C_a = 2\,\pi\, n\, T \times 1 \cdot 356\,;$$

where T is given in pound-feet; n in revolutions per second; E the whole volts generated by the armature; and C_a = whole amperes flowing through the armature. But E is proportional to the speed if the magnetism is constant, the fundamental expression for it being (see pp. 46 and 170) for an ordinary two-pole machine,

$$E = n\, Z\, \mathsf{N} \div 10^8\,;$$

where Z is the number of conductors around the armature, and **N** the magnetic flux through its core. Inserting this value for E, and cancelling n from both sides, we get:

$$\frac{Z\, \mathsf{N}\, C_a}{1 \cdot 356 \times 10^8} = 2\,\pi\, T\,;$$

whence

$$\frac{Z\, \mathsf{N}\, C_a}{8 \cdot 52 \times 10^8} = T \text{ (in pound-feet).}[1]$$

From this it appears that if in a given machine the magnetism is constant, the torque depends in no wise upon the speed, but only upon the current flowing through the armature, and on the magnetism.

These expressions apply equally to dynamos and to motors. They show that if it is desired to build slow-speed machines provision must be made for a very large magnetic flux; for only by making **N** large can the dynamo at slow speed yield the requisite volts, or the motor exert the needful torque.

A number of curves, called *mechanical characteristics*, giving

[1] If T is desired in metre-kilogrammes, the divisor on the left must be replaced by the value $61 \cdot 5 \times 10^8$.

the relations between speed and torque in a number of different cases, will be found in Chapter XX.

Drag on Armature Conductors.—We are now in a position to understand the drag on the armature. Setting aside for the moment the case of embedded conductors, we may at once proceed to calculate the amount of such drag. There are three methods of doing this: two being electrical and one a purely mechanical calculation.

METHOD I.—By the last formula the torque is calculated; and from this the total peripheral force is found by dividing by the known radius of the armature. Hence the force per conductor is obtained by dividing the number of active conductors.

Example in the Edison-Hopkinson dynamo (Fig. 287), $C_a = 326$; $Z = 80$; $N = 10{,}850{,}000$; radius $= 0{\cdot}458$ feet; whence $T = 332$ pound-feet, and total peripheral force $= 724{\cdot}7$ lbs. This would give about 9 lbs. average force per conductor if all were active; but only about 58 of them are in the magnetic field at one time; hence, the average force per conductor is about $12\frac{1}{2}$ lbs. If the magnetic field in the gap-spaces is not uniform there comes a stronger drag on those conductors which lie in the densest field.

METHOD II.—The drag on a conductor of length l, in a magnetic field of intensity H, carrying current of C amperes, is

$$f \text{ (dynes)} = C\,l\,H \div 10.$$

This formula[1] is only applicable if H, the density of the field in the gap-space, is known. If l'' and $H_{''}$ are given in inch measures (see p. 126), the formula becomes

$$f \text{ (lbs.)} = C\,l''\,H_{''} \div 11{,}303{,}000.$$

Example, as before: Current in any one conductor will be $\frac{1}{2}\,C_a = 163$ amperes; $l'' = 20''$, and $H_{''} =$ about 43,300 lines per square inch, the area of the gap-space being about 250 square inches. Whence drag on each conductor $= 12{\cdot}49$ lbs.

[1] To give f in kilogrammes, the divisor 10 must be replaced by 9,810,000.

METHOD III.—Ascertain actual horse-power on armature; multiply by 33,000 to reduce to foot-pounds per minute, and divide by the peripheral speed (in feet per minute). [The horse-power may be reckoned from the electrical output as on p. 102] Then divide by the number of active conductors. Or, in symbols,

$$f \text{ (lbs. average drag per conductor)} = \frac{\text{H.P.} \times 33{,}000}{\text{ft. per min.} \times Z}.$$

Example, same as before: Since $i_a = 326$, and $E = 108{\cdot}5$ volts, $\text{H.P.} = 326 \times 108{\cdot}5 \div 746 = 47{\cdot}45$. Also periphery $= 2\pi \times$ radius $= 2{\cdot}88$ feet. This, at 750 revs. per minute, gives 2158 feet per minute as peripheral speed. Assuming fifty-eight conductors to be active, we get

$$\text{av. force on each conductor} = \frac{47{\cdot}45 \times 33{,}000}{2158 \times 58} = 12{\cdot}5 \text{ pounds.}$$

A convenient approximate rule may be given as follows:—If we assume, as a sort of rough average for the magnetic field in the gap-space of a dynamo or motor, the value of 40,000 lines to the square inch, or say 6300 lines per square centimetre, then *the drag per inch of conductor will be* 0·00354 *pound for each ampere of current carried.* In alternate-current dynamos the intensity of the field is seldom more than half as great as this.

Such, then, is the drag that magnetic fields exert upon non-embedded armature conductors; and, it must be remembered that the drag is not a steady one. When the conductor emerges from the gap-space, though there is still a current in it, the magnetic drag is taken off. Twice, therefore, in each revolution this drag is suddenly removed and suddenly put on again, increasing the racking action. In the case of alternate-current machines, where the relation of phase between the currents and the magnetic fields complicates the matter, the drag is not simply taken off and put on twice in each complete period, but is actually reversed; the armature conductors being driven with a back drag on them, then experience a forward drag and tend to drive, then once more are driven,

and again tend to drive as the current reverses. In the alternate current machine acting as generator the intermediate forward drags are slight and of short duration; in the machine acting as motor it is the backward drags that are of short duration.

It must further be remembered that the conductors of the rotating armature are also subject to centrifugal force, and must be strongly held in with external binding-wires, or wedged in between the tips of the teeth, if not carried through holes in the core-disks.

Need of Driving Horns.—It is then obvious that under the mechanical conditions now described, if the conductors are not embedded in the iron cores there is need of a good positive method of conveying the driving power to them from the shaft. In the dynamo it is they that need to be driven. In the motor, it is they that drive the shaft. The question of construction is complicated by the consideration that whilst the copper conductors must be mechanically connected to the shaft in the most positive way, they must not be metallically connected, but on the contrary, must be insulated therefrom. Different constructors adopt different modes of accomplishing the end in view. Some makers key on to the shaft a strong hub provided with spokes that project beyond the surface of the core-disks, and protected by layers of adequate insulation, thus drive the copper conductors. Others secure the core-disks mechanically to the shaft, and insert wedges of wood or of hard fibre into nicks in the periphery to serve as driving-horns. In cases where toothed core-disks are used, no other driving-horns are necessary. Compare the practical modes adopted by modern makers described in Chapter XIII.

Stray Power.—In the preceding paragraphs it has been assumed that the mechanical power applied *at the shaft* to drive the armature was equal to the electrical power actually generated in the armature. The power to be applied at the pulley is, however, always greater than this; for, in the first place, some of the applied power is lost by friction in the bearings, &c., and never reaches the armature. But of that

which actually reaches the armature, not all is actually converted into electrical power. There are, beside the friction at the bearings and brushes, three sources of loss, viz.: (1) air-friction, (2) hysteresis, (3) eddy-currents. The first of these is insignificant, except in those cases where curved spokes are employed with the object of making the armature act as a fan, and even then is small. The second is by no means negligible, but seldom adds more than 1 or 2 per cent. to the driving power. The third is the most important of all, especially in large machines. In all the moving metal masses, unless laminated, there will be eddy-currents set up if they cut magnetic lines. Even in the metal of the shaft, power may be lost from this cause if there is leakage of magnetic lines into it. The mode of investigating the separate sources of loss is described in Chapter XXX. on the Testing of Dynamos and Motors. Whatever these losses, it is evident that they all call upon the supply of power: for the power supplied is necessarily equal to the sum of the power actually converted in the armature into electric power, and the stray power wasted in the ways enumerated.

Efficiency of Dynamos and Motors.—Efficiency is a term used in several senses, which it is well to distinguish.

(1) *Efficiency of Conversion* or *Gross Efficiency*, is the relation between the gross electrical power actually converted in the armature, and the gross mechanical power imparted by belt or coupling to the shaft. If 12 per cent. of the gross mechanical power is lost in friction at the bearings, friction at the brushes, air-friction, hysteresis, and eddy-currents, then the remaining 88 per cent. being actually converted in the armature, we should describe the efficiency of conversion as 88 per cent.

(2) *Electrical Efficiency*, or *Economic Coefficient*, is the ratio between the nett electric power or nett output of the dynamo, and the gross electric power, or power actually converted in the armature. Thus, if in a shunt dynamo 3 per cent. of the gross electric power is wasted in heating the resistance of the armature, and another 3 per cent. is wasted in maintaining

the magnetizing current in the shunt winding, the output or nett electric power will be only 94 per cent. of the gross electric power; or the electrical efficiency is 94 per cent. This ratio depends only on the resistances of the machine. In modern machines it may even attain 97 per cent.

(3) *Commercial Efficiency*, or *Nett Efficiency*, is the ratio between the nett electrical output and the gross mechanical power supplied by belt or coupling. It is therefore equal to the product of the efficiency of conversion and the electrical efficiency. In the example given it is 94 per cent. of 88 per cent., or 82·72 per cent.

Relation of Size to Capacity and Efficiency.

There has been considerable controversy upon the relation that subsists between the linear dimensions of similar machines and their permissible output and their efficiency; the divergence of views arising mainly as to the assumptions that are suitable at the outset. A few things are certain; for example, the power of getting rid of the heat is only proportional to the surface. It is generally safe to assume that peripheral speeds will not vary much between large machines and small. Amongst those who have discussed the problem are Hopkinson, Frölich, Ayrton, Mascart and Joubert, Kapp, Storch, Rechniewski, and Pescetto. According to Hopkinson[1] the capacity of similar machines is proportional to the *cube* of their linear dimensions; the work wasted in magnetizing the field-magnets is proportional to the linear dimensions, whilst that wasted in heat in the armature conductors is proportional to the square of the linear dimensions. Mascart and Joubert[2] place the capacity as low as the *square* of the linear dimensions, and draw the conclusion that small machines are preferable to large ones. Pescetto[3] arrives at similar conclusions. Rech-

[1] *Proc. Inst. Civil Engineers*, April 1883.
[2] *Leçons sur l'Électricité* (1886), ii. 815.
[3] *L'Électricien*, xi. 357, 1887.

niewski[1] follows Hopkinson in assigning n^3 as the proportional increase in the capacity of a machine if its linear size is increased n times. Frölich[2] assigns the value n^4, and criticizes the rule of the fifth power given in 1882 by the author of this work and by Deprez, as involving an increase of n^3 in the current whilst there is an increase of only n^2 in the section of the conducting wires, which is clearly impracticable. Storch[3] considers constant-current machines to be in a different category from constant-potential machines. Assuming equal intensity of magnetic-field, equal peripheral velocity, and equal permissible current density, he finds that in all machines the ampere-turns requisite for excitation vary as the linear dimensions. For constant-current machines the capacity is proportional to n^3, that is to say to the weight of the machine, or to the volume of copper on the armature. For constant-potential machines he finds the total length of wire on the armature to be independent of the dimensions of the machines; the number of external armature conductors to vary inversely as the linear dimensions; whilst the capacity of the machines is found to vary as n^4, though with undue heating, unless the volume of copper on the armature is also increased as n^4. Storch and Rechniewski agree with Hopkinson that the work lost in field-magnets decreases relatively to that lost in armatures, with an increase in the linear dimensions. On the other hand, increase in the size of the moving masses increases the liability to waste of power by eddy-currents. Kapp[4] proposes that the speeds of rotation shall be assumed to vary inversely as the linear dimensions, so as to put all machines into equal conditions as regards strains from centrifugal force, and that all the similar machines shall be considered as being worked up to the same safe limit of heating. This involves that the work wasted internally in heat shall be proportional to surface or as $1 : n^2$.

[1] *La Lumière Électrique*, xxii. 311.
[2] *Die dynamoelektrische Maschine* (1886), p. 168.
[3] *Centralblatt für Elektrotechnik*, viii. 544, 594, and 743, 1886.
[4] *Proc. Inst. Civil Engineers*, lxxxiii. 36, 1886.

The resistances, both magnetic and electric, of the field-magnets will be proportional to n^{-1}, and the exciting powers to $n^{\frac{3}{2}}$. The intensities of field will be proportional to $n^{\frac{1}{4}}$, and the electromotive-forces to $n^{1\frac{1}{4}}$. The diameters of wires allowed are as n^1 on the magnets and $n^{\frac{3}{4}}$ on the armatures; the resistances of armatures will be proportional to n^{-2}, and the permissible current to n^2. It follows at once that the capacities of the machine (in watts) will vary as $n^{3\frac{1}{4}}$, whilst the work wasted will vary as n^2: hence the economic coefficient will increase with the size of the machine. Kapp gives the cost of machines as proportional to $n^{2\frac{1}{4}}$, whence it follows that the cost of a dynamo per lamp varies inversely as its linear dimensions. He gives the following illustrative table:—

Diameter of armature (inches)	10	15
Revolutions per minute	1000	670
Number of glow-lamps	150	620
Weight (in tons)	0·5	1·7
Price	100*l.*	276*l.*
Price per lamp	13*s.* 4*d.*	8*s.* 11*d.*
Electrical efficiency (per cent.)	80	89

Ayrton[2] assumes that the speeds of similar machines may be safely put as inversely proportional to the square-roots of the linear dimensions or as to $n^{-\frac{1}{2}}$ instead of n^{-1}. In the larger machines the smaller relative space required for clearance makes admissible the increase of the current in proportion to n^2. But this increased current would magnetize the iron more highly in proportion, and the electromotive-force would be greater than $n^{1\frac{1}{4}}$, probably nearer $n^{1 \cdot 7}$, bringing up the capacity to be proportional to $n^{3 \cdot 7}$.

The common opinion of dynamo constructors appears to be that the capacity of dynamos is, for similar machines, a little greater than in proportion to the weight.

Esson[2] has discussed this question from the point of view of multipolar machines, and finds it a matter of appropriate design whether the efficiency increases or decreases when

[1] *Proc. Inst. Civil Engineers*, 116, 1886.

[2] *Journ. Inst. Electrical Engineers*, xix. 164, 1890, and xx. 265, 1891.

machines are enlarged in size. He also points out that in increasing all linear dimensions there is greater relative interference of the armature, tending to produce sparking and so to limit the output. He therefore concludes that the output will not be proportional to weight, *i.e.* to n^3, unless with the larger sizes the surface-speed is somewhat increased.

CHAPTER VI.

MAGNETIC PRINCIPLES; AND THE MAGNETIC PROPERTIES OF IRON.

As all dynamo-electric machines are based on magnetic principles, it is needful that these should be understood fully. If we once know the relation that subsists between the exciting current and the magnetism that is produced by it, we can apply this knowledge to the design of dynamos: for such knowledge will enable us to calculate beforehand the size of field-magnet and the number and gauge of windings that will be required in a dynamo that is to furnish any given amount of electric energy. It will be necessary first to define the terms used; then we shall give some account of the facts relating to the magnetic circuit, and of the properties of iron and steel of different kinds. In Chapter VII. follow the method of calculating the reluctance of the magnetic circuit; some examples and useful rules will be given; and lastly, the various forms given to field-magnets will be discussed, and calculations respecting them given.

DEFINITIONS AND GENERAL PROPERTIES.[1]

Unit Magnetic Pole.—The unit magnetic pole is one of such a strength, that when placed at a distance of 1 centimetre

[1] It is strongly recommended that the reader should make himself familiar with the elementary theory of magnetic phenomena. The author's *Elementary Lessons in Electricity and Magnetism*, published by Messrs. Macmillan and Co., will explain the terms and fundamental facts. The author's work on *The Electromagnet*, published by Messrs. Spon, contains a fuller account of the magnetic properties of iron, and the design and construction of electromagnets. Prof. Ewing's work on *Magnetic Induction in Iron and other Metals* is a standard book of reference.

(in air) from a pole of equal strength, it repels it with a force of 1 *dyne*.

Intensity of Magnetic Field.—We have seen in Chapter III. that every magnet is surrounded by a certain "field," within which magnetic force is observable. We may completely specify the properties of the field at any point by measuring the *strength* and the *direction* of that force—that is, by measuring the "*intensity of the field*" and the direction of the lines of force. *The "intensity of the field" at any point is measured by the force with which it acts on a unit magnetic pole placed at that point.* Hence, *unit intensity of field is that intensity of field which acts on a unit pole with a force of one dyne.* There is therefore a field of unit intensity at a point one centimetre distant from the pole of a magnet of unit strength. Suppose a magnet pole, whose strength is m, placed in a field at a point where the intensity is H, then the force will be m times as great as if the pole were of unit strength, and the amount of the force (in dynes) can be calculated by simply multiplying together the strength of the magnetism of the pole and the intensity of the field ; or,

$$f = m \times \mathsf{H}.$$

Magnetic Lines.—It is possible, in every magnetic field, to draw through any given point, a line in such a direction that it represents the direction of the magnetic force at that point of the field (Fig. 10, p. 24). The iron filing curves formed round magnets show the forms of the otherwise invisible magnetic lines. Even when such lines are not actually drawn, they may be supposed to be drawn ; we may even conceive the whole of the space in the magnetic field to be traversed by such lines. Faraday was the first to give a quantitative signification to the conception of magnetic lines. We may use them to specify not only the *direction*, but also the *magnitude* of the magnetic forces by adopting the following convention :—Let there be drawn as many lines per square centimetre of cross section of the field as there are dynes of force (on a unit pole) at the point in question. The symbol H may then be read to mean *either* the number of dynes on a unit pole, or the number

of lines per square centimetre in air; it also may, as we shall presently see, be read to mean the amount of magnetomotive-force exerted, per unit length, along the field.

The convention of magnetic lines enables us to see more clearly what is meant by *magnetic flux;* for looking at Fig. 10, we see the lines issuing from one pole of the magnet like a stream spreading out over the surrounding space and flowing in at the opposite pole. Just as the total number of stream-lines of a liquid remains the same throughout the whole path, so the total number of lines of a magnet passing through a section of the path is the same whatever section we take, provided that our section cuts across the whole of the path. This total number is called the *magnetic flux,* and is symbolized by the letter N. The lines pass through the bar-magnet, Fig. 10, as well as the surrounding space, and thus make a complete *magnetic circuit.* If the ends of the bar were bent round and joined, so as to form a completely continuous ring, then all the lines would circulate within the metal of the magnet, and none in the air surrounding it. We should then speak of the ring as a *closed magnetic circuit.* In the dynamo we try to attain this metallic continuity of the circuit as nearly as possible, consistently with the movability of the rotating parts.

Though the definition of a magnetic line in the air is connected with the force upon a magnetic pole, we are not so much concerned (while considering dynamos), with the forces (exerted on poles by the lines), as with that other phenomenon, the induction of an electromotive-force when a conductor is moved across the lines. Indeed, though we have said that the magnetic lines are continuous throughout the entire circuit, it is really only in so far as their property of generating an electromotive-force is concerned, that they can be regarded as continuous; for the force inside a magnetic material, such as iron, is not represented by the number of magnetic lines per square centimetre, as will be shown when we come to speak of magnetomotive-force. It is only in air, and equally non-magnetic substances that the force is represented by the number of lines per square centimetre. We therefore rather

use the expression "magnetic lines," when speaking of the flux through magnetic material, in contrast to "the lines of force" which emerge into the air. The two are continuous throughout the circuit, and in the air the magnetic lines are the lines of force. Where the lines which represent the direction and amount of any vector quantity, as, for example, magnetic lines or lines of electric flow, are closed on themselves so as to form a circuit, the distribution of the vector quantity is said to be *circuital.* The number of magnetic lines per centimetre of cross section of the magnetic material is aptly called the *flux-density*, and is usually denoted by B. The magnetic force in the material is as before denoted by H, which in fact represents the number of magnetic lines that would exist in the space if the magnetic material were replaced by air while the same causes producing magnetization still existed.

The idea of a magnetic circuit was more or less familiar to Ritchie,[1] Sturgeon,[2] Dove,[3] Dub,[4] and De la Rive,[5] the last-named of whom explicitly uses the phrase "a closed magnetic circuit." Joule[6] found the maximum power of an electromagnet to be proportional to "the least sectional area of the entire magnetic circuit," and he considered the resistance to induction as proportional to the length of the magnetic circuit. Faraday[7] considered that he had *proved* that each magnetic line constitutes a closed curve; that the path of these closed curves depended on the magnetic conductivity of the masses disposed in proximity; that the magnetic lines were strictly analogous to the lines of electric flow in an electric circuit. He spoke of a magnet surrounded by air being like unto a voltaic battery immersed in water. He even saw the existence of a power, analogous to that of electro-

[1] *Phil. Mag.*, series iii. vol. iii. 122.

[2] *Ann. of Electr.*, xii. 217.

[3] *Pogg. Ann.*, xxix. 462, 1833. See also *Pogg. Ann.*, xliii. 517, 1838.

[4] Dub, *Elektromagnetismus*, p. 401 (ed. 1816); and *Pogg. Ann.*, xc. 440, 1853.

[5] De la Rive, *Treatise on Electricity* (Walker's translation), i. 292.

[6] *Ann. of Electr.*, iv. 59, 1839; v. 195, 1841; and *Scientific Papers*, pp. 8, 34, 35, 36.

[7] *Experimental Researches*, vol. iii. arts. 3117, 3228, 3230, 3260, 3271, 3276, 3294 and 3361.

motive-force in electric circuits, though the name *magneto-motive-force* is of more recent origin. The same idea is more or less implicitly recognised in the latter half of the magnetic papers in Lord Kelvin's collected volume on Electrostatics and Magnetism. Rowland[1] in 1873 expressly adopted the reasoning and language of Faraday's method in the working out of some new results on magnetic permeability, and pointed out that the flow of magnetic lines of force through a bar could be subjected to exact calculation; the elementary law, he says, "is similar to the law of Ohm." Writing R for the "resistance to lines of force," M for "magnetizing force of helix," and Q for number of "lines of force in a bar at any point," he wrote, for a particular case (a ring-magnet, having therefore a closed magnetic circuit), the equation,

$$Q = \frac{M}{R};$$

an equation for magnetic circuits which every electrician will recognise as being precisely like Ohm's law. He applied the calculations to determine the permeability of certain specimens of iron, steel and nickel. In 1882,[2] and again in 1883,[3] Mr. R. H. M. Bosanquet brought out at greater length a similar argument, employing the extremely apt term "Magneto-motive Force," to connote the force tending to drive the total flux of magnetic lines through the "magnetic resistance" (or reluctance) of the circuit. In these papers the calculations were reduced to a system, and deal not only with the specific properties of iron, but with problems arising out of the shape of the iron. Bosanquet showed how to calculate the several reluctances of the separate parts of the circuit, and then add them together to obtain the total reluctance of the magnetic circuit.

[1] *Phil. Mag.*, series iv. vol. xlvi. August 1873. "On Magnetic Permeability and the Maximum of Magnetism of Iron, Steel, and Nickel."

[2] *Proc. Roy. Soc.*, xxxiv. 445, December 1882.

[3] *Phil. Mag.*, series v. vol. xv. 205, March 1883. "On Magneto-motive Force." Also *ibid.*, vol. xix. February 1885; and *Proc. Roy. Soc.*, No. 223, 1883. See also *Electrician*, xiv. 291, February 14th, 1885.

In 1886, Mr. Gisbert Kapp,[1] and independently Drs. J. and E. Hopkinson,[2] introduced magnetic-circuit calculations into the designing of dynamo-electric machines. These methods we shall further consider in the next chapter.

We have seen that N, the magnetic flux from pole to pole of the field-magnet, is an important quantity in the determination of the electromotive-force of a dynamo. Since this total flux depends on (i.) the magneto-motive force, and (ii.) the reluctance of the magnetic circuit, it is necessary to give some consideration to these two quantities.

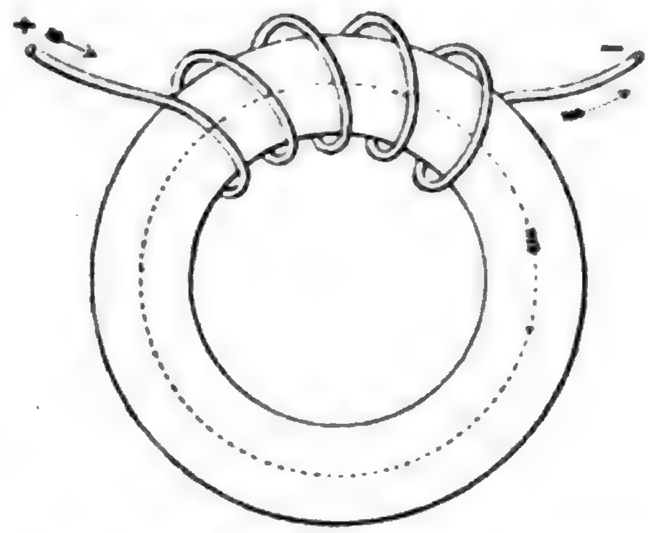


FIG. 82.—MAGNETIZING COIL WOUND AROUND A MAGNETIC CIRCUIT.

1. *Magnetomotive-Force* or Total Magnetizing Power of Electric Current circulating in a Coil.—It is found that when a current flows along in a wire that is coiled in several turns around a core (Fig. 82), and is thus made to circulate around an interlinked magnetic circuit, the magnetizing power is proportional both to the strength of the current so circulating and to the number of turns in the coil. The magnetizing power is independent of the size or material of the wire, and of its shape, and is the same whether the spirals are close together or wide apart. If S stands for the number of *spirals* in the coil, and C be the number of *amperes* of current that are flowing, then C multiplied by S will be the number of *ampere-turns* of circulation of current. It is experimentally proved that twenty amperes circulating around five turns exert precisely

[1] *Journal Soc. Telegraphic Engineers and Electricians*, xv. 524-529, November 11th, 1886. "On the Predetermination of the Characteristics of Dynamos"; a very valuable paper marred by mixed units. Those who wish to study examples of this mode of calculating, will find some examples in a paper communicated by Professor Jamieson in Jan. 1889, to the *Institution of Engineers and Shipbuilders in Scotland*; vide *Electrician*, March 1, 1889.

[2] *Phil. Trans.*, part i. p. 331, 1886.

the same magnetizing power as one ampere circulating one hundred times, or as one hundred amperes circulating once around the core. In each of these cases the circulation of current is one hundred ampere-turns. To calculate from this the value, in absolute C.G.S. units, of the magnetomotive-force, it is requisite to multiply the ampere-turns by $\frac{4}{10}\pi$, or by $1 \cdot 257$. Or, in symbols,

$$\text{Magnetomotive-force} = 1 \cdot 257 \times C\,S.$$

It is possible to avoid the use of this multiplier by taking the ampere turns themselves as the magnetomotive-force. In that case one applies a coefficient to the calculation of the reluctance of the circuit (see p. 146).

Some writers[1] call the magnetomotive-force the "line-integral of the magnetic forces." The reason is as follows:—In a field of intensity H, a unit magnetic pole experiences a force numerically equal to H; and if the unit were moved against this force once around a closed path of length l (like the dotted line in Fig. 82), the work done would measure the integral magnetic force. Hence along a length l in a field of intensity H the magnetomotive-force is equal to $\mathsf{H} \times l$. Hence it also follows that the intensity of the field along a uniformly wound coil is expressed by the formula :—

$$\mathsf{H} = 1 \cdot 257 \times C\,S \div l.$$

In other words H is proportional to the ampere-turns per unit of length.

There are some analogies between a magnetic circuit and an electric circuit, which considerably simplify the magnetic principles relating to dynamo construction.[2]

Just as there are some materials which conduct the electric

[1] See Maxwell's *Electricity and Magnetism*, vol. ii. art. 499; or S. P. Thompson's *Elementary Lessons on Electricity and Magnetism* (edition of 1895), p. 334.

[2] It should be observed that, though for the purpose of this simplification, it is allowable to draw an analogy between an electric circuit and a magnetic circuit, the true magnetic analogue of an electric circuit (in which energy is being continually transported) would be a circuit in which energy is being transported by the passage of "free magnetism;" but no conductors of magnetism in this sense are as yet known.

current better than others, so there are some materials which conduct the magnetic flux better than others. The reluctance or resistance of a circuit in each case is proportional to the length of the path, to the reluctivity or resistivity of the material, and inversely proportional to the cross section of the path. Just as in a battery the total electromotive-force is made up of the separate electromotive-forces of all the cells joined in series, so the total magnetomotive-force in a magnetic circuit is the sum of the magnetomotive-forces separately produced by each coil of wire. If the magnetic circuit is branched (as in the Manchester dynamo shown in Fig. 101, No. 24), then the coils on the separate branches do not have their forces added together, but are analogous to batteries placed in parallel with each other.

We have a difference of magnetic potential between the ends of core wound with a magnetizing coil just as we have a difference of electric potential at the terminals of a cell. As we go along the magnetic circuit the potential falls by an amount equal to the reluctance of the path multiplied by the total flux. The iron inside a magnetizing coil may be said to be for the purpose of diminishing its "internal" reluctance. We have stout iron frames for our dynamos in order that the magnetic pressure of the coils may be transferred to the armature without appreciable "drop." The fall of magnetic potential in a column of air per centimetre of length is numerically equal to the flux-density. Therefore, to calculate the magnetomotive-force necessary to create a certain flux-density in a certain air-space, we have only to multiply the flux-density by the length of the air-space.

Thus to produce a flux-density of 10,000 lines per square centimetre in an air-gap 1 centimetre in length will require a magnetic pressure of 10,000 *gausses*, a gauss being the magnetomotive-force required to produce unit flux-density in an air-space 1 centimetre in length.[1] One ampere-turn produces a magnetomotive-force of 1·257 gausses, so that to produce a flux-density of 10,000 in an air-gap 1 centimetre

[1] It requires 2·54 *gausses* or 2·02 ampere-turns to produce unit flux-density in an air-space 1 inch in length. See note on p. 144.

in length will require $\frac{10,000}{1 \cdot 257}$ ampere-turns. We might calculate the ampere-turns required on a dynamo field-magnet by multiplying the flux-density by the total length of air-gap and dividing by $1 \cdot 257$, and then add some further turns to make up for the drop in magnetic potential in the iron circuit; but it is more usual to find the total reluctance of the circuit and multiply by the total flux in the manner shown in Chapters VII. and XVI.

2. *Reluctance of Magnetic Circuit.*—We have seen that, other things being equal, the total flux in a circuit is inversely proportional to the reluctivity of the materials of which it is composed; it is directly proportional to the *permeability* which is the reciprocal of *reluctivity.*

The permeability of a material is the numerical coefficient which expresses the ratio between flux-density B, and the magnetizing force[2] H. For instance, if a column of air is subjected to a magnetizing force H, the number of magnetic lines per square centimetre of cross section, in other words the flux-density B, is equal to H; therefore, the ratio $\frac{B}{H} = 1$ and we say the permeability of the air is 1. If we take a piece of iron and subject it to the same magnetizing force H we find

[2] The following are the various ways of expressing the three definitions:—

B—The number of lines per square centimetre in the material.
The flux-density.
The magnetic displacement.
The internal magnetization.
The magnetic induction.
The induction.
The intensity of the induction.
The permeation.

H—The number of lines per square centimetre that there would be in air.
The magnetizing force at a point.
The magnetic force at a point.
The intensity of the magnetic force.
The rate per cm. of fall of magnetic potential.
The magnetomotive-force per unit length.

μ—The magnetic permeability.
The permeability.
The specific conductivity for magnetic lines.
The magnetic multiplying power of the material.

that B is very much greater. For example, a certain specimen of iron, when subjected to a magnetic force capable of creating, in air, 50 magnetic lines to the square centimetre, was found to be permeated by no fewer than 16,062 magnetic lines per square centimetre. Dividing the latter figure by the former gives 321 as the value of the permeability, that is to say, the permeability of the iron at this stage of the magnetization is 321 times that of air. The permeability of such non-magnetic materials as silk, cotton and other insulators, also of brass copper and all the non-magnetic metals, is taken as one, being practically the same as that of the air.

The permeability of iron, however, varies very greatly with the degree to which it has been magnetized. In all kinds of iron (after passing the initial stage mentioned below) the magnetizability of the material becomes diminished as the actual magnetization is pushed further; there is in fact a tendency to magnetic saturation. In other words, when a piece of iron has been magnetized up to a certain degree, it becomes, from that degree onward, less permeable to further magnetization, and though actual saturation is never reached, there is a practical limit beyond which the magnetization cannot well be pushed. Joule was one of the first to establish this tendency toward magnetic saturation. Modern researches have shown numerically how the permeability diminishes as the magnetization is pushed to higher stages. The practical limit of the flux-density, B, in good wrought iron, is about 20,000 magnetic lines to the square centimetre, or about 125,000 lines to the square inch; and in cast iron the practical saturation limit is nearly 12,000 lines per square centimetre, or about 70,000 lines per square inch.

In designing electromagnets, before calculations can be made as to the size of a piece of iron required for the core of a magnet for any particular purpose, it is necessary to know the magnetic properties of that piece of iron; for it is obvious that if the iron be of inferior magnetic permeability, a larger piece of it will be required in order to produce the same magnetic effect as might be produced with a smaller piece of higher permeability. Or again, the piece having inferior

permeability will require to have more copper wire wound on it; for in order to bring up its magnetization to the required point, it must be subjected to higher magnetizing forces than would be necessary if a piece of higher permeability had been selected.

Curves of Magnetization.

A convenient mode of studying the magnetic facts respecting any particular brand of iron is to plot on a diagram the curve of magnetization—*i. e.* the curve in which the values, plotted horizontally, represent the magnetic force, H, and the values plotted vertically those that correspond to the respective flux-density, B.

Thirty-five samples of various irons of known chemical composition were examined by Hopkinson,[1] the two most important for present purposes being an annealed wrought iron and a grey cast iron, such as are used by Messrs. Mather and Platt in the construction of dynamo machines. Hopkinson embodied his results in curves, from which it is possible to construct, for purposes of reference, numerical tables of sufficient accuracy to serve for future calculations.

The upper curve, Fig. 83, gives the behaviour of annealed wrought iron.[2] The ascending line shows the relation between the intensity of the magnetizing force H and the flux-density B during the process of increasing the magnetizing force from zero to about 220; and the descending line shows the same relation during the process of decreasing the magnetizing force to zero, and then reversing it so as to remove the residual magnetic lines. The lower curve shows the behaviour of *grey cast iron.*

Every sample of iron will show, on being tested, a similar set of facts which can be plotted down as a curve that is characteristic of the relation in question; but the curves for cast iron and steel always lie lower than those for wrought iron. Moreover, it will usually be noticed that when a fresh piece of iron or steel is subjected to a gradually increasing

[1] *Phil. Trans.*, pt. ii. p. 455, 1885.
[2] Hopkinson in *Phil. Trans.*, pt. ii. 455, 1885.

magnetizing force, the lowest part of the curve presents near its origin a small concavity (see Fig. 83), showing that there is a certain stage where under small magnetizing forces the permeability is greater than at the initial stage. This concavity is more pronounced in the case of hard iron and of steel than in the case of soft iron. But the curves differ in detail even in different specimens of the same sort of iron. In

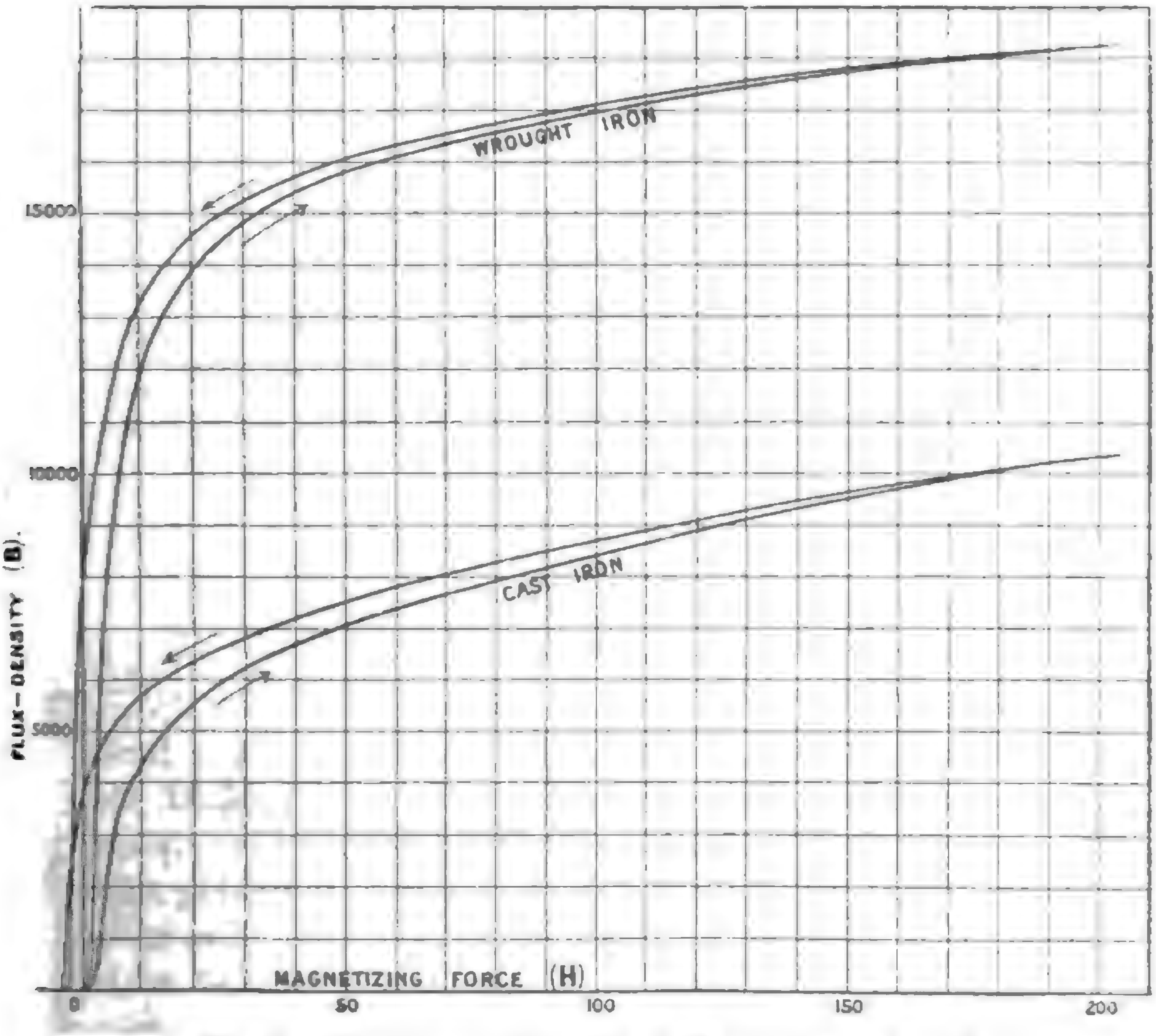


FIG. 83.—HOPKINSON'S CURVES OF MAGNETIZATION OF IRON.

designing dynamos it is convenient to have for reference a series of curves such as Fig. 84, made by observation on samples of the same iron as it is intended to use in construction.

In Fig. 84 are given seven curves,[1] relating to soft iron, hardened iron, "mild steel,"[2] annealed steel, hard-drawn steel, cast iron and glass-hard steel.

[1] *Phil. Trans.*, 1885. [2] See p. 127 as to the nature of so-called "mild steel."

If we plot a curve taking the permeability $\frac{B}{H}$, or, as it is usually denoted, μ, for ordinates, and B for abscissæ, we have the results in a more convenient form for reference when making calculations of magnetic reluctances. Fig. 85 gives curves of various materials plotted in this way. The curve marked annealed soft iron is plotted from results obtained by Hopkinson from a carefully annealed specimen of soft iron. The values for B, μ and H for this specimen are given in square centimetre units in Table I., and in square inch units in Table II.

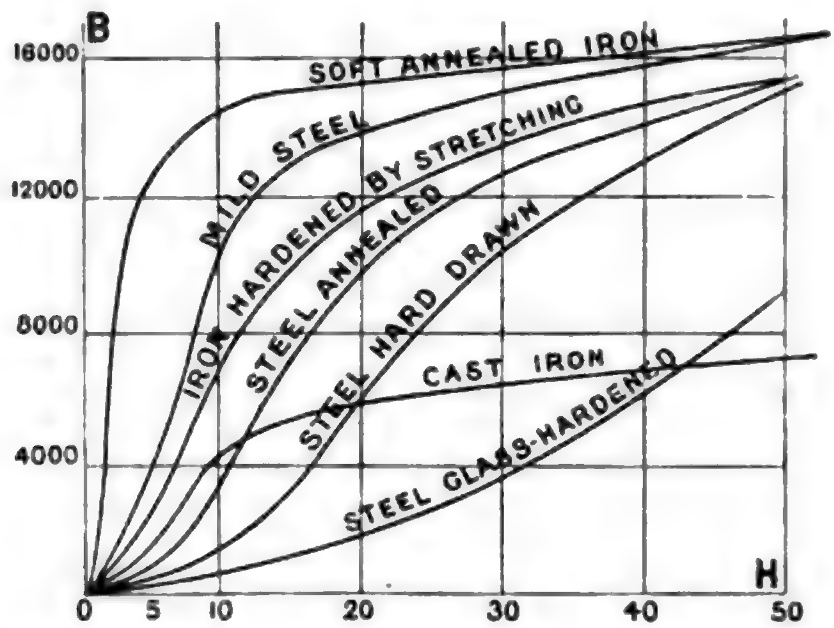


FIG. 84.—CURVES OF MAGNETIZATION OF VARIOUS SORTS OF IRON.

This curve is characteristic of the behaviour of the best Swedish iron. Beneath is a curve given by Prof. D. C. Jackson,[2] showing the average results obtained from three specimens of good quality merchant wrought iron having the following percentage of impurities: C = 0·075, Si = 0·1, Mn = 0·25, P = 0·1, S = 0·1. It will be seen that with wrought iron the permeability, for small flux-densities, is not very great, but increases as the density is increased up to about 5000. An increase beyond this point decreases the permeability until when B = 16,000 the permeability has fallen to 400, and at B = 20,000 it is about 100. Thus it is not economical to push B much beyond 16,000. In dynamo field-magnets B is generally somewhere about 16,000, so that

[1] *Electromagnetism and the Construction of Dynamos* (Macmillan).

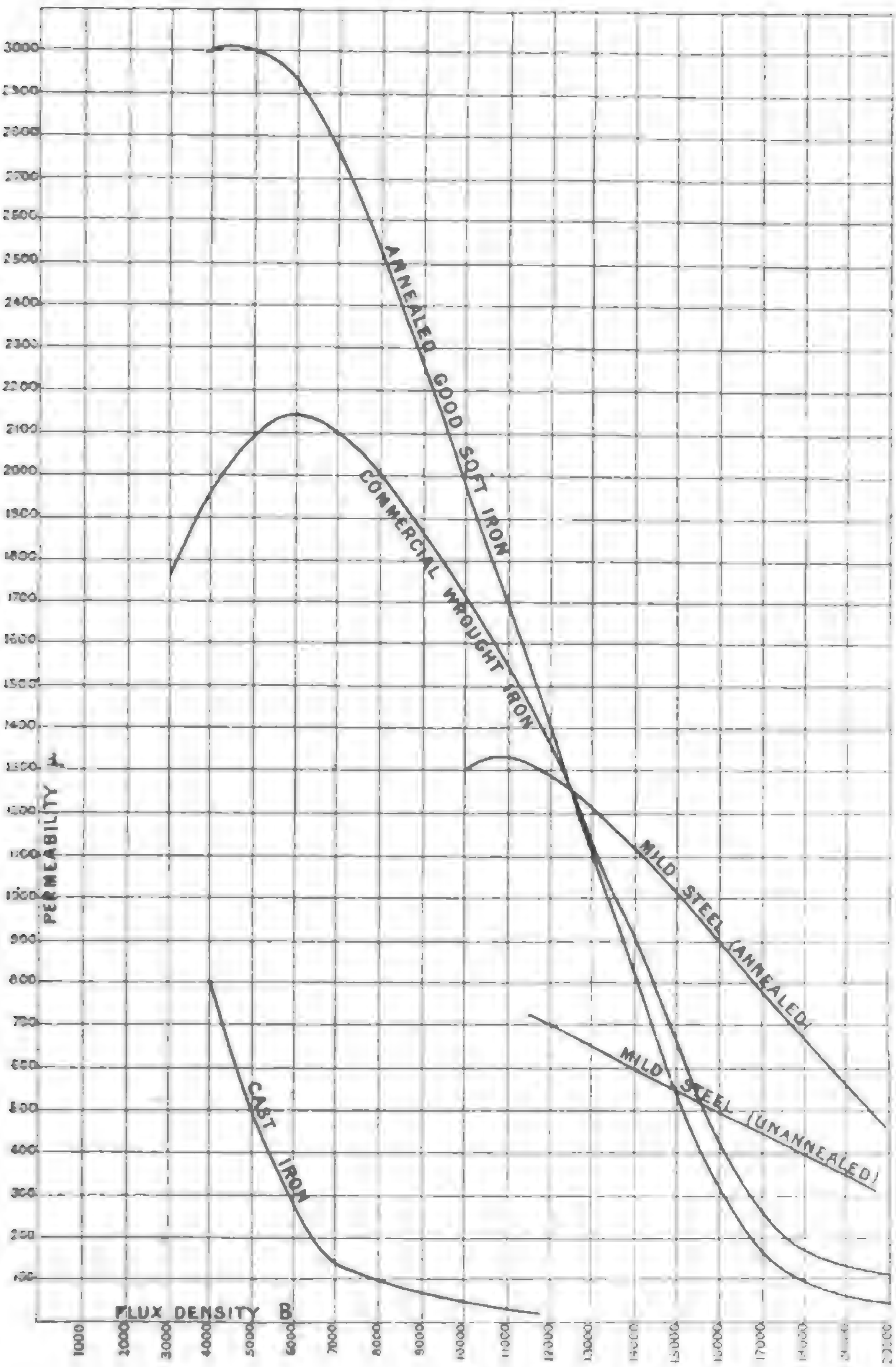


FIG. 85.—CURVES CONNECTING FLUX-DENSITY AND PERMEABILITY IN VARIOUS MATERIALS.

TABLE I. (SQUARE CENTIMETRE UNITS).

Annealed Wrought Iron.			Grey Cast Iron.		
B	μ	H	B	μ	H
5,000	3000	1·66	4,000	800	5
9,000	2250	4	5,000	500	10
10,000	2000	5	6,000	279	21·5
11,000	1692	6·5	7,000	133	42
12,000	1412	8·5	8,000	100	80
13,000	1083	12	9,000	71	127
14,000	823	17	10,000	53	188
15,000	526	28·5	11,000	37	292
16,000	320	50			
17,000	161	105			
18,000	90	200			
19,000	54	350			
20,000	30	666			

TABLE II. (SQUARE INCH UNITS).

Annealed Wrought Iron.			Grey Cast Iron.		
$B_{\prime\prime}$	μ	$H_{\prime\prime}$	$B_{\prime\prime}$	μ	$H_{\prime\prime}$
30,000	2926	10·2	25,000	833	30
40,000	2857	14	30,000	445	53·5
50,000	2392	20·9	40,000	245	163
60,000	2166	27·7	50,000	112	447
70,000	1750	40	60,000	64	940
80,000	1368	63	70,000	40	1750
90,000	856	105			
100,000	407	245			
110,000	161	686			
120,000	64	1850			
130,000	28	4500			
140,000	18	7630			

the permeability of the material at this point is the criterion of the value of different materials for field-magnets. Now, looking at the curve for *mild cast steel*, it will be seen that, though the permeability for flux-densities of the order of 10,000 is very much lower than the permeability of iron, yet at great flux-densities the mild steel is equally good or even better than wrought iron. Being much cheaper, it has come very much into use in dynamo construction. Though this material is known as mild steel,[1] it is in reality much more allied to iron in its composition, as it contains only about 0·2 per cent. of carbon and is incapable of taking a temper. The facts that it can be cast and is soft to tool greatly facilitate the construction of dynamo frames of mild steel. *Mitis metal*, which is a sort of cast wrought iron, being a wrought iron rendered fluid by addition of a small percentage of aluminium, is, as the author has found, more magnetizable than cast iron, and not far inferior to the best wrought iron.

Hammering, rolling, chilling, or any process which tends to physically harden iron will lessen its permeability, but the evil effects of such processes may be destroyed by raising the metal to a red heat and allowing it to cool very slowly. The effect of this annealing is shown in the curves.

The curve for cast iron varies a great deal with the quality. Generally speaking, the permeability is decreased in proportion to the amount of carbon present in the combined state.

For an account of the various methods of measuring[2] the

[1] For data upon mild steel and mitis metal, see G. Henrard, *La Lumière Électrique*, xxxiii. 595; and Thompson, Knight and Bacon, *Amer. Inst. Elec. Engs.*, ix. June 7th, 1892.

[2] Consult also the following works:—

Ewing, J. A., various papers in the *Philosophical Transactions* of the Royal Society in the years 1885 to 1894. A full résumé is given in his book *Magnetic Induction in Iron and other Metals*. London, 1894.

Hopkinson, Dr. J., papers in the *Philosophical Transactions* of the Royal Society, 1885 to 1895. Those of chief importance are reprinted in his book.

Du Bois, H. J. G., *Magnetische Kreise, deren Theorie und Anwendungen*. Berlin, 1894.

Jackson, Dugald C., *Electromagnetism and the Construction of Dynamos* (Macmillan).

magnetic qualities of iron, see the author's treatise on *The Electromagnet.*

This is not the place to enter upon the modern molecular theory of magnetism propounded by Ewing. Those who would follow out this most important topic must refer to Ewing's published works.

EFFECTS OF AIR-GAP IN MAGNETIC CIRCUIT.

All the preceding results refer exclusively to that which goes on in iron itself, the curves of magnetization referring to the magnetic materials only. But if there is an air-gap in the

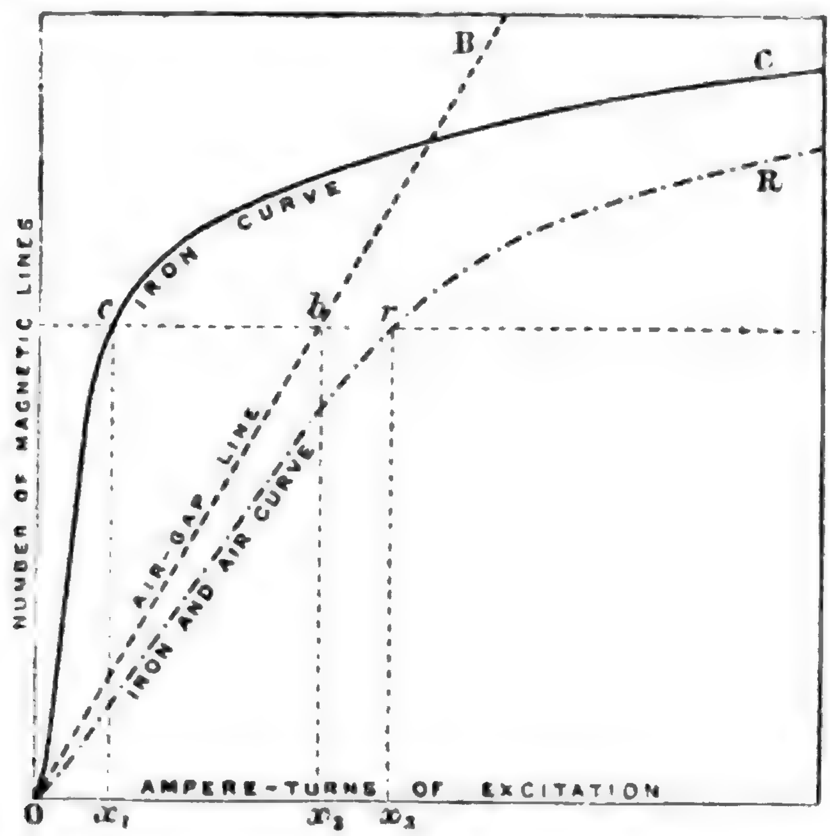


FIG. 86.—CURVE OF MAGNETIZATION OF MAGNETIC CIRCUIT WITH AIR-GAP.

magnetic circuit, or a gap filled with any non-magnetic material (possessing a permeability = 1), it is evident that to force the same number of magnetic lines across a layer of such inferior permeability will necessitate an increase in the magnetomotive-force that must be applied.

This is made plainer by reference to Fig. 86, in which the curve O c C represents the relation between the number of

magnetic lines in an iron bar and the number of ampere-turns of excitation ($H\,l \div 1 \cdot 257$) needed to force this flux through the iron. For example, to reach the height c, the excitation has to be of the value represented by the length $O\,x_1$. On the same diagram the line $O\,b\,B$ represents the relation between the magnetic flux across the air-gap and the ampere-turns required to force this flux across. If the gap were 1 cm. long, 0·795 ampere-turns of current would produce field $H = B = 1$. In this case the gap is supposed to be shorter than 1 cm., the line sloping up at such a slope that the length $O\,x_2$ represents the ampere-turns requisite to bring up the magnetic flux to b, which is at the same height on the scale as c. It is then easy to put the two things together, for the total amount of excitation required to force these magnetic lines through air and iron will (neglecting leakage) be the sum of the separate amounts. The point x_3 is chosen so that $O\,x_3$ is equal to the sum of $O\,x_1$, and $O\,x_2$, or that the distance of point r from the vertical axis is equal to the sum of the respective distances of c and b. If the same thing is done for a large number of corresponding points, the resultant curve $O\,r\,R$ may be constructed from the two separate curves. It will be seen then that, in general, the presence of a gap in the magnetic circuit has the effect of causing the magnetic curve to rake over, *the initial slope being determined by the air-gap.*

Effect of Joints.

Being now in a position to calculate the additional magnetizing power required for forcing magnetic lines across an air-gap, we are prepared to discuss a matter that has been so far neglected, namely, the effect of joints in the iron on the reluctance of the magnetic circuit.

It is a matter purely for experiment to determine how far a transverse plane of section across the iron obstructs the flow of magnetic lines. This matter has been examined by Professor J. J. Thomson and Mr. Newall, in the Cambridge Philosophical Society's *Proceedings*, in 1887; and more fully by Professor Ewing, whose researches are published in the

K

Philosophical Magazine for September 1888. Ewing not only tried the effect of cutting and of facing up with true plane surfaces, but used different magnetizing forces, and also applied various external pressures to the joint. For our present purpose we need not enter into the questions of external pressures, but will summarize in Table III. the results which Ewing found when his bar of wrought iron was cut across by section planes, first into two pieces, then into four, then into eight. The apparent permeability of the bar was reduced at every cut.

TABLE III.—EFFECT OF JOINTS IN WROUGHT-IRON BAR (not compressed).

H	B				Mean thickness of equivalent air-space for one cut.		Thickness of iron of equivalent reluctance per cut.	
	Solid.	Cut in Two.	In Four.	In Eight.	Centimetres.	Inches.	Centimetres.	Inches.
7·5	8,500	6,900	4,809	2,600	0·0036	0·0014	4	1·57
15	13,400	11,550	8,900	5,550	0·0030	0·0012	2·53	1
30	15,350	14,550	12,940	9,800	0·0020	0·0008	1·10	0·433
50	16,400	15,950	15,000	13,300	0·0013	0·0005	0·43	0·169
70	17,100	16,840	16,120	15,200	0·0009	0·0004	0·22	0·087

Suppose we are working with the magnetization of our iron pushed to about 16,000 lines to the sq. cm., referring to Table III., we see that each joint across the iron offers as much reluctance as would an air-gap 0·0005 of an inch in thickness, or adds as much reluctance as if an additional layer of iron about $\frac{1}{6}$th of an inch thick had been added. With small magnetizing forces the effect of having a cut across the iron with a good surface on it is about the same as though you had introduced a layer of air $\frac{1}{600}$th of an inch thick, or as though you had added to the iron circuit about 1 inch of extra length. With large magnetizing forces, however, this disappears, probably because of the attraction of the two surfaces across that cut. The stress in the magnetic circuit, with high magnetic forces running up to 15,000 or

20,000 lines to the sq. cm., will of itself put on a pressure of 130 to 230 lbs. to the square inch, and so these resistances are considerably reduced; they come down in fact to about $\frac{1}{20}$th of their initial value.

The above results of Ewing's are further represented by the curves of magnetization drawn in Fig. 87. When the

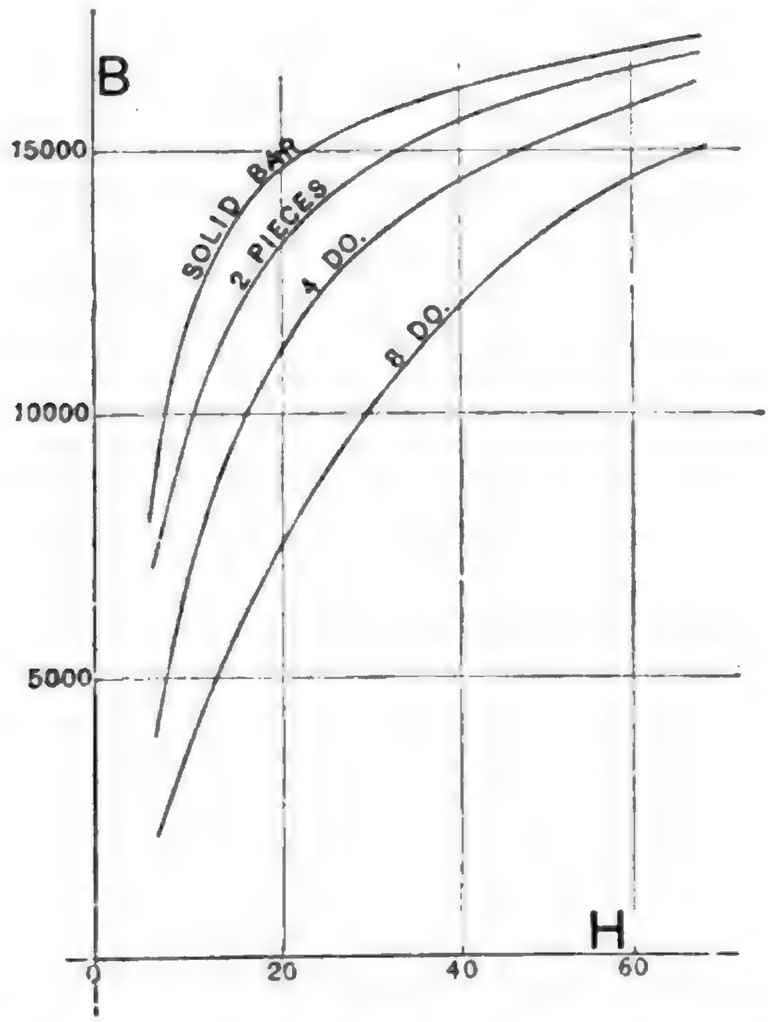


FIG. 87.—EWING'S CURVES FOR EFFECT OF JOINTS.

faces of a cut were carefully surfaced up to true planes, the disadvantageous effect of the cut was reduced considerably, and under the application of a heavy external pressure almost vanished.

EFFECTS OF HEAT.

When iron in a strong magnetic field is raised to a temperature above 600° C. it begins to lose its magnetic qualities, and at 780° C. they entirely disappear. At temperatures between 0° and 100° the effect of heat is so small that for all practical purposes it may be neglected.

RESIDUAL MAGNETISM.

It is well known that several kinds of magnetic materials —lodestone, steel, particularly hardened steel, and hard sorts of iron—exhibit residual magnetism after having been subjected to magnetic forces. It is also known that closed circuits of soft iron—even of the very softest—will exhibit a considerable amount of residual magnetism so long as the circuit which they constitute is unbroken. A very simple illustration of this is afforded by any electromagnet possessing in its core and well-fitting armature a compact magnetic circuit. If it is excited by passing a current, which is then quietly turned off, the armature usually does not drop off, and may even require considerable force to detach it; but when once so detached will not again adhere, the residual magnetization having almost entirely disappeared. In like manner a steel horse-shoe magnet, if magnetized powerfully while its keeper is across its poles, may become "supersaturated"; that is to say, magnetized to a higher degree of magnetization than it can retain in permanence, a portion of this residual magnetization disappearing the first time the keeper is removed.

Reference to Fig. 83 will show that when the magnetizing force H is gradually increased from zero to a high value, and is then gradually decreased to zero, the resulting internal magnetization B first increases to a maximum, and then decreases, but does not come back to zero. The curve descending from the maximum does not coincide with the ascending curve. In fact, when the magnetizing force has been entirely removed there remained (in this specimen) a residual magnetization of about 47,000 lines to the sq. in., or about 7300 lines per sq. cm. It has been proposed to give the name of the *remanence* to the number of lines per sq. cm., that thus remain as the residual value of B. To remove this *remanence,* a negative magnetizing force must be applied. Suppose enough magnetizing force has been used, the curve will descend and cut the horizontal axis at a point to the left of the origin; and with greater negative magnetizing forces,

the specimen will begin to be magnetized with magnetic lines running through it in the reversed direction. The particular value of the negative magnetizing force which is needed to bring the remanent magnetization to zero has been termed by Hopkinson *the coercive force.* In the specimen of wrought iron in question the coercive force (in C.G.S. measure) is about 2. The force thus required to deprive any specimen of its remanent magnetization may be taken as a measure of the tendency of iron of this particular quality to retain permanent magnetism. Hard kinds of iron and steel always show more coercive force than soft kinds of iron. For example, whilst that of soft wrought iron is about 2, that of hard steel may be as much as 50.

HYSTERESIS.

Professor Ewing, who has particularly studied the residual effects exhibited by various qualities of iron and steel, has given the name of *hysteresis* to this tendency of the effects to lag, in phase, behind the causes that produce them. The appropriate mode of studying hysteresis is to subject the specimen to a complete cycle (or to a number of successive cycles) of magnetizing forces. For example, let the magnetizing force begin at zero, and increase to a high value (say to H = 200) and then decrease back to zero, then reverse and increase to a high negative value, and finally return to zero. Such a cycle is given in Fig. 88, which is taken from Ewing's researches, and relates to a series of experiments made with a piece of annealed steel pianoforte wire. The curve begins in the centre of the diagram, and as H is increased positively, the curve rises at first concavely to the right, then turns over, and when H = 90, B has risen to a little over 14,000. When H is then reduced back to zero the curve turns back on itself, but does not fall as fast as it previously rose, for when H is reduced to 20, B has gone down only to 12,000, and when H = 0 the remanence is about 10,500. If at this point H had been again increased to 90, B would have run up again to 14,000, as shown by the thin line. If, however, the magnetizing force is reversed, the curve descends to the left, and

cuts the horizontal axis at − 24, which is therefore the value of the coercive force. On increasing the reversed magnetizing force to H = − 90, the reversed magnetization increases to the value B = − 14,000, or a little more. Then when these reversed magnetizing forces are reduced to zero, the curve returns towards the right, crossing the vertical axis at B = − 10,500 (the negative remanence); and on re-reversing the magnetizing force it is found that when H = + 24, the

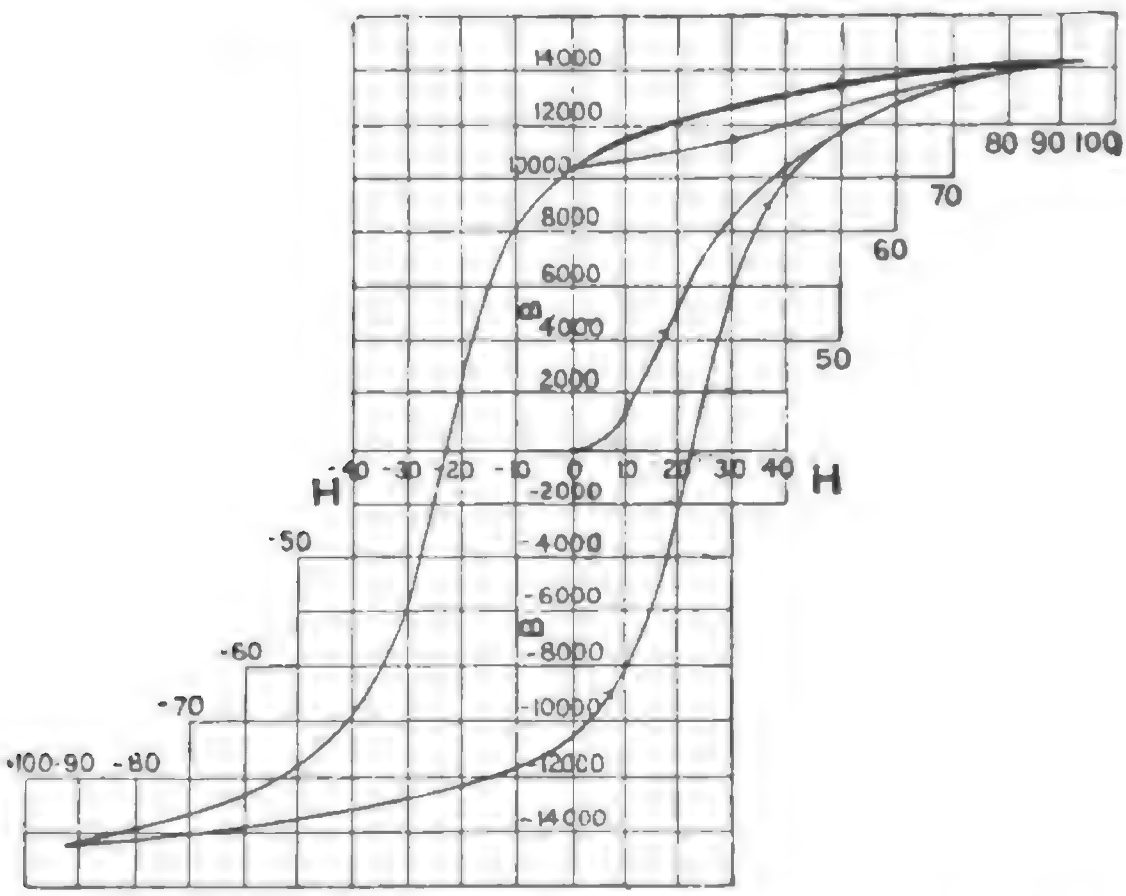


FIG. 88.—CYCLE OF MAGNETIC OPERATIONS ON ANNEALED STEEL WIRE.

magnetization is once more zero. After this point, increasing H causes the magnetization to run up very rapidly, not quite following its former track, but coming up as before to the apex, when H is raised to the same maximum of 90.

CYCLES OF MAGNETIZATION.

Such cycles of magnetization as that which has just been described, if carried out on any specimen of iron or steel, always yield curves that exhibit, like Fig. 88, an enclosed

area. This fact has been shown by Warburg[1] and by Ewing[2] to possess a special significance, for the area enclosed is a measure of the work wasted, per unit of volume of the iron, in carrying the iron through a complete cycle of magnetiza-

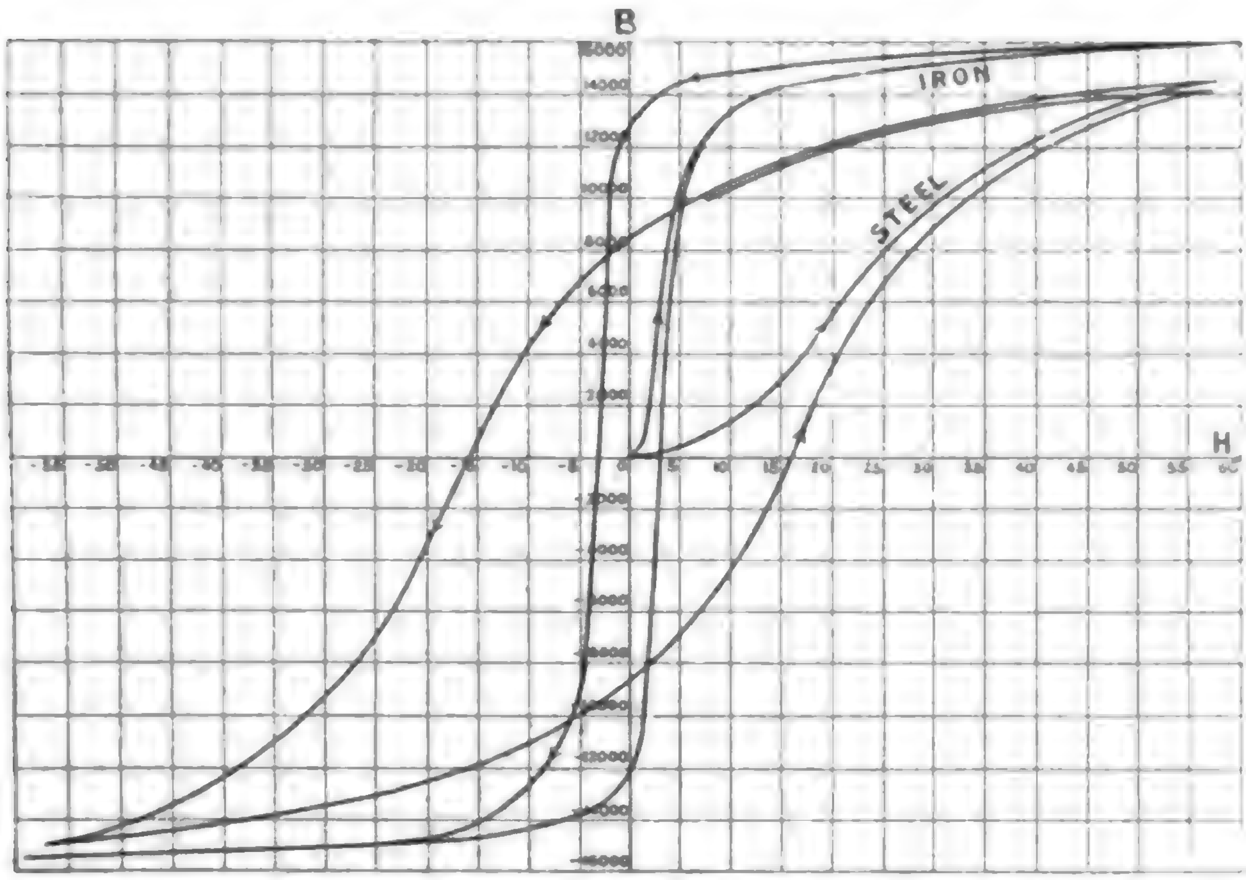


FIG. 89.—HYSTERESIS IN WROUGHT IRON AND IN STEEL.

tions. Just as the area traced out on the indicator-card of a steam engine is a measure of the heat transformed into useful work in the cycle of operations performed by the engine, so in this magnetic cycle the area enclosed by the curve is a measure of the work transformed into (useless) heat.[3]

[1] *Wied. Ann.*, xiii. 141, 1881.

[2] *Proc. Roy. Soc.*, xxxi. 22, 1881; xxxiv. 39, 1884; and xxxv. 1, 1885; and *Phil. Trans.*, 1885, pt. ii. 523.

[3] The proofs of these matters are as follows. In a magnetic field of strength H it will require H units of work to move a unit of magnetism along a length of 1 centimetre against the magnetizing forces. Hence, since there are 4π magnetic lines to each unit of magnetism, the work done in one complete cycle on a single cubic centimetre of the iron will be equal to $\frac{1}{4\pi}\int H\,dB$. If H and B are in C.G.S. units, the work will be given in ergs per cubic centimetre. Hence if this number is multiplied by the number of cycles per second and divided by 10^7, the result will express the number of watts of power wasted.

For the sake of comparison, a curve for wrought iron and one for steel are given side by side in Fig. 89. In all these cases the closed area represents the work which has been wasted or dissipated in subjecting the iron to these alternate magnetizing forces. In very soft iron, where the ascending and descending curves are close together, the enclosed area is small; and as a matter of fact, very little energy is dissipated in a cycle of magnetic operations. On the other hand, with hard iron, and particularly with steel, there is a great width between the curves, and there is great waste of energy. The energy lost per cycle depends not only upon the nature of the material but also upon the degree to which the magnetization is carried in each cycle—in fact, upon the *amplitude* of the cycle.

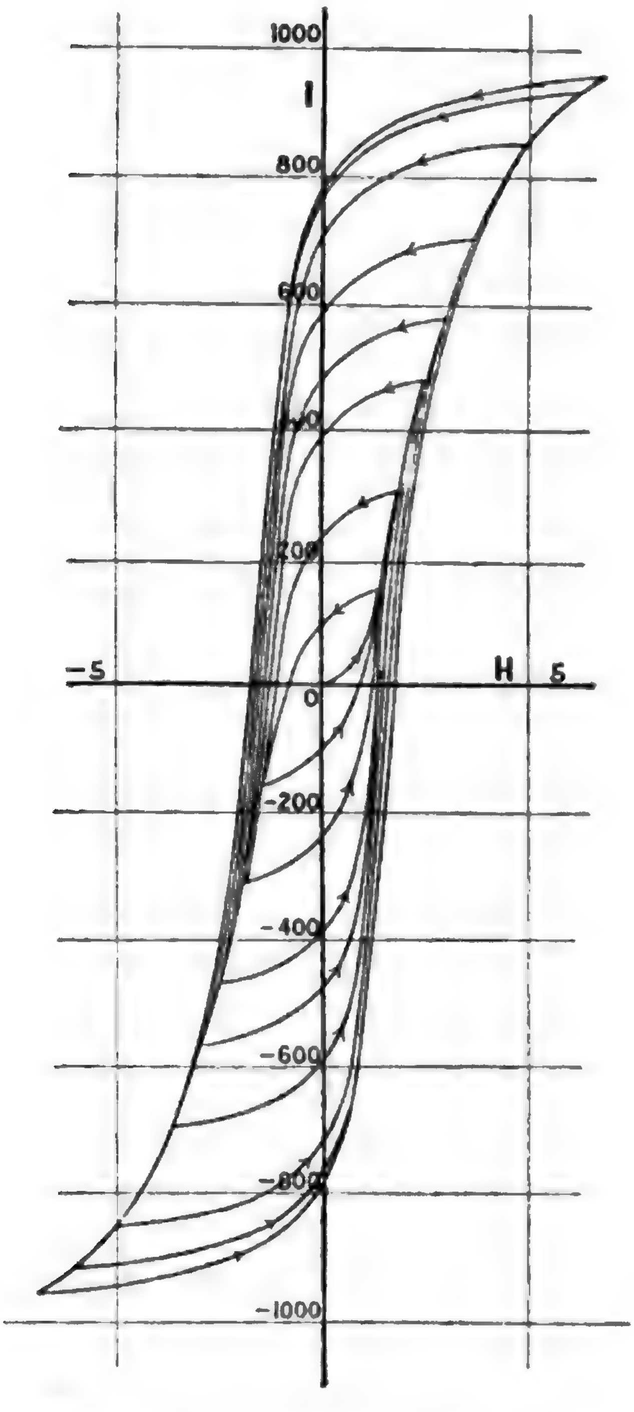


Fig. 90.—Successive Cycles of increasing Amplitudes.

Fig. 90, taken from J. A. Ewing's researches,[1] shows the effect of subjecting a piece of soft annealed iron wire to a graded series of reversals beginning with weak forces, and gradually increasing the force until the limits of H were ± 7 C.G.S. As the amplitude of the cycle is increased the area of the cyclic curve increases in a greater ratio—in other

[1] *Phil. Trans.*, 1885, p. 555.

words, the loss of energy per cycle is more than proportionally great when B is increased.

Mr. C. P. Steinmetz[1] has given the following law connecting the hysteresis loss h in ergs per cubic centimetre of iron per cycle and the flux-density B. He finds that

$$h = \eta B^{1 \cdot 6}$$

where η is a constant called the hysteretic constant depending upon the kind of iron. This law is true for cycles performed either slowly or as rapidly as 200 per second. The following table gives the hysteretic constant η for different materials[2] when ordinary frequencies are employed.

HYSTERETIC CONSTANTS FOR DIFFERENT MATERIALS.

Material.	Hysteretic Constant η.	Material.	Hysteretic Constant η.
Very soft iron wire	·002	Soft annealed cast steel ..	·008
Very thin soft sheet iron ..	·0024	Soft machine steel	·0094
Thin good sheet iron ..	·003	Cast steel	·012
Thick sheet iron	·0033	Cast iron	·016
Most ordinary sheet iron	·004	Hardened cast steel ..	·025
Transformer cores	·0045		

From experiments with actual transformer plates at n cycles per second the hysteretic loss in watts per cubic centimetre of iron was found to be

$$W = 0 \cdot 0033 \times 10^{-7} \times n \times B^{1 \cdot 6}.$$

Besides the hysteretic loss in transformer plates, there is also a loss due to eddy currents in the iron. This varies as the square of the thickness of the iron, the square of the frequency, and the square of the flux-density. Fleming has obtained by calculation the formula

$$Y = X^2 B^2 n^2 10^{-16},$$

[1] *Amer. Inst. Elec. Engineers*, Jan. 19th, 1892; *Electrician*, Feb. 12th, 19th and 26th, 1892.

[2] For particulars of Ewing's Magnetic Tester for measuring Hysteresis in sheet iron, see *Inst. Elec. Engineers*, April 25th, 1895, also *Electrician*, xxxiv. 786.

Y being the loss in watts per cubic centimetre of core made up of the strip, and X being the thickness of the strip in mils. Thus we have the total loss in watts due to both hysteresis and eddy currents—

$$W = 0{\cdot}0033\, n\, \mathrm{B}^{1\cdot 6} \times 10^{-7} + X^2\, \mathrm{B}^2\, n^2 \times 10^{-16}.$$

This has been found to agree very closely with practice.

If, as in a transformer, the iron is carried through a certain number of cycles per second, we have a continual loss which

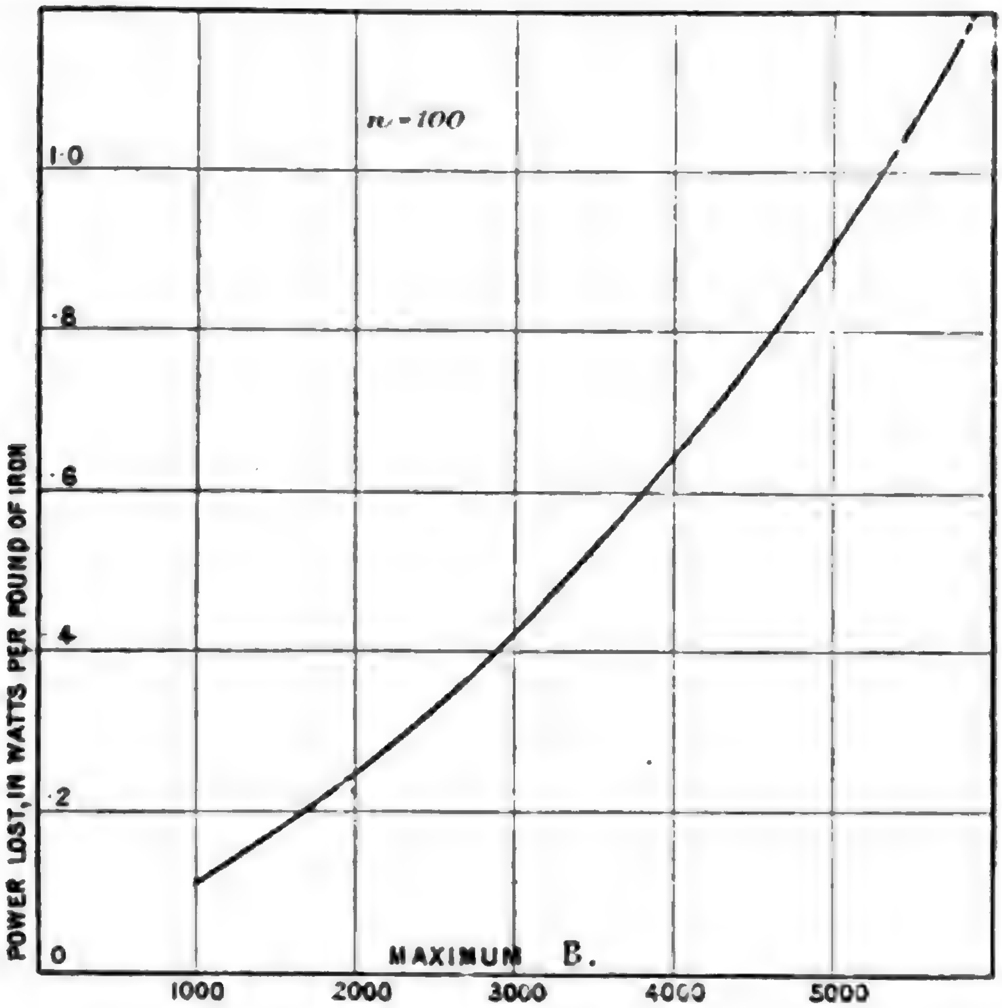


FIG. 91.

can be measured in watts per lb. of iron, for the amount of waste depends upon the quantity of iron magnetized.

Plotting the loss in watts per lb. of iron with the maximum flux-density B, the curve[1] (Fig. 91) shows an ever increasing slope. From this it appears that it is not economical to carry B to a very high value in transformers. The most economical value depends upon a variety of circumstances

[1] Kapp, *Journ. Inst. Elec. Engineers*, xxiii. 207, 1894.

such as the frequency of supply, the amount of waste allowable, and the first cost of the transformer. A flux-density of 4000 is very usual. It must be remembered that by increasing the flux-density we can decrease the cross-section of the iron, and thus the total weight of iron employed, and this up to a certain point reduces the loss, although the loss per pound is increased. Another inducement to increase the flux-density in a transformer is the fact that for very small flux-densities the permeability of the iron is less than for the flux-densities of about 7000. The curve in Fig. 92 shows how the per-

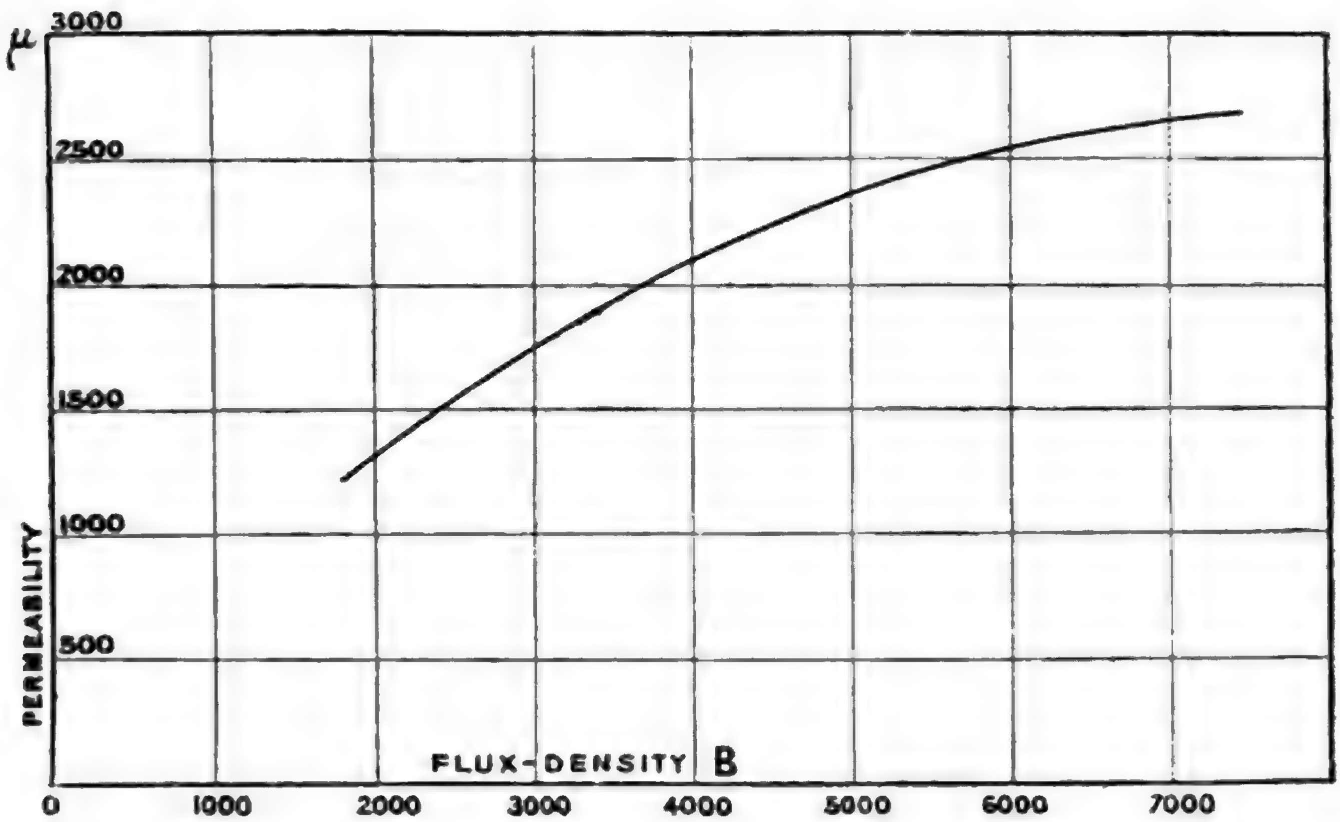


FIG. 92.—PERMEABILITY CURVE FOR TRANSFORMER-IRON.

meability of transformer-iron increases, as the flux-density is increased up to about 7000; after this point the curve is flat, and then descends again as higher densities are reached. This fact can indeed be seen from the curves in Fig. 90, for the slope of a line joining the peak of any cyclic curve to the origin gives the permeability of the iron for that cycle so far as it affects the magnetizing current required in a transformer. By increasing the permeability we make a considerable saving in the energy required to magnetize.

The following table gives the number of watts wasted by

hysteresis in well-laminated soft wrought iron when subjected to a succession of rapid cycles of magnetization.

WASTE OF POWER BY HYSTERESIS.

B	B_H	Watts wasted per cubic foot at 10 cycles per second.	Watts wasted per cubic foot at 100 cycles per second.
4,000	25,800	40	400
5,000	32,250	57·5	575
6,000	38,700	75	750
7,000	45,150	92·5	925
8,000	51,600	111	1110
10,000	64,500	156	1560
12,000	77,400	206	2060
14,000	90,300	262	2620
16,000	103,200	324	3240
17,000	109,650	394	3940
18,000	116,100	487	4870

Ewing has given the following values of the energy wasted in a magnetic cycle of strong magnetization on various brands of iron and steel :—

WASTE OF ENERGY BY HYSTERESIS.

Brand experimented upon.	Ergs per cubic centimetre lost in one complete cycle of magnetization.
Very soft annealed iron	9,300
Less soft ,, ,, ...	16,300
Hard drawn iron wire	60,000
Annealed steel wire	70,500
Glass hard steel wire	76,000
Pianoforte steel wire (ordinary state)	116,000
,, ,, (annealed)	94,000
,, ,, (glass hard)	117,000

Hopkinson found that oil-hardened tungsten steel, the sort chosen for making permanent magnets because of its great

coercive force, wasted no less than 216,864 ergs per cubic cm. per cycle. He has pointed out that the area of a curve like Fig. 88 is approximately equal to a rectangle, the height of which is double the remanence, and the breadth of which is double the coercive force.

Ewing has shown that vibration tends to destroy residual effects. Also Dr. Finzi has found[1] that iron cores whilst traversed by an alternating electric current show no hysteresis, the ascending and descending curves of magnetization coinciding. There is also some evidence that with very rapid frequencies there is less work wasted per cycle than there would be in the same cycle performed slowly.

When an armature core is rotated in a strong magnetic field the magnetization of the iron is being continually carried through a cycle, but in a manner quite different from that in which it is carried when the magnetizing force is periodically reversed, as in the core of a transformer. Mordey has found[2] the losses by hysteresis to be somewhat smaller in the former case than in the latter.

Magnetic Creeping.—Another kind of after-effect was discovered by Ewing, and named by him "viscous hysteresis." This is the name given to the gradual creeping up of the magnetization when a magnetic force is applied with absolute steadiness to a piece of iron. This gradual creeping may go on for half-an-hour or more, and amount to several per cent. of the total magnetization. This is a true, but slow, magnetic lag, and must not be confounded either with the lag of phase discussed already under the name hysteresis, or with the apparent lag due to the retardation of the magnetizing current resulting from self-induction, or with the apparent lag observable in unlaminated iron cores due to eddy-currents circulating in the mass of the iron itself.

Retardation of Magnetization.—It has long been known that in solid cores of electromagnets the rise and fall of the magnetism is retarded by eddy-currents in the iron, the outside part of the iron becoming magnetized first when the current is

[1] *Electrician*, xxvi. 72, April 3, 1891.

[2] See also Ewing, in *Electrician*, xxvii. 602, 1891.

turned on; whilst the magnetism of the inner parts grows up later when the eddy-currents in the outer part die away. There is thus a regular penetration or propagation of the magnetism from the outer to the inner parts of the core. When the magnetizing-current is cut off the inner part is the last to lose its magnetism. In large dynamos many minutes may elapse before the magnetism attains its maximum. For this reason the author pronounced it useless to put a compound winding upon dynamos with large solid electromagnets for use as electric railway generators. It is even possible for the mid-core of an electromagnet to have a magnetization of reverse direction to that of the outer layers. The phenomenon of magnetic retardation in solid cores has lately been investigated by Dr. J. Hopkinson and Mr. E. Wilson,[1] using an iron-clad electromagnet with a core 12 inches in diameter with exploring coils buried at different depths in its substance. Hopkinson showed that the retardation varies as the square of the linear dimensions. He also investigated the effect when the magnetizing force was alternated in periodic cycles, and found that the depth to which the magnetizations penetrate depends upon the frequency (see Chapter XXII.).

Slow Changes in the Magnetic Properties of Iron.—When iron is magnetized for a long time by rapidly alternating currents, its magnetic properties undergo a slight change, so that the amount of energy absorbed in carrying it through a given magnetic cycle is increased. This effect has been observed in connection with the working of transformers on alternate-current systems, and is due to a physical change in the iron, which affects its permeability or its hysteresis loss, or both. Whether the change is due directly to the continual reversal of magnetization or whether it is a secondary effect caused by the heating, and by the compression that takes place with the expansion of the iron through heat, is not certainly established, but a series of experiments carried out by Mr. W. M. Mordey,[2] point to the latter cause as being sufficient to account for the phenomenon.

[1] *Journ. Inst. Elec. Engineers*, Feb. 1895, and *Philos. Trans.*, 1895.
[2] *Proc. Roy. Soc.*, lvii. 1894.

Approximate Formulæ for the Law of the Electromagnet.

Before the discovery of the law of the magnetic circuit, many attempts were made to find a working formula to express the amount of magnetism which is produced in a given electromagnet by an exciting current of any particular value. Of these an elaborate account is given in the second and third editions of this book. As they are not now used in dynamo designing, they may be very briefly dismissed.

The earliest suggestion of Lenz and Jacobi was a simple proportion between the exciting current and the magnetism produced. This is equivalent to saying that the curve of magnetization is a straight line sloping upwards from the origin. Joule showed that this law was not true; that with sufficient magnetizing power saturation set in. Müller (followed by Von Waltenhofen, Kapp and others) proposed an arc-tangent formula; suggesting that if the exciting current be represented by the length of a straight line drawn as a tangent to a circle, then the arc which it subtends will represent the amount of magnetism which results. This gives a saturation limit, but fails to represent the facts in the earlier stages of magnetization. Lamont, from theoretical considerations, proposed an exponential formula, from which he deduced an approximate expression equivalent to the statement that the permeability is at all stages proportional to the difference between the actual amount of magnetism and its possible maximum amount. Lamont's formula was revived by Frölich,[1] and largely used in various forms by various writers, including the author of this book. Let us make the supposition that the magnetic flux N will have at complete saturation a maximum value $\bar{\mathsf{N}}$, and that the magnetizability of the magnet at any stage is proportional to the room left for magnetic lines, that is to $\bar{\mathsf{N}} - \mathsf{N}$. Now, writing S for the number of spirals and C for the current flowing in them, we get S C for the ampere-turns of exciting power, and $\mathsf{N} \div \text{S C}$ will be the ratio of magnetism to magnetizing power or magnetizability. We may then write

$$\frac{\mathsf{N}}{\text{S C}} = \frac{\bar{\mathsf{N}} - \mathsf{N}}{h},$$

[1] *Elektrotechnische Zeitschrift*, pp. 90, 139, 170, 1881, and p. 73, 1882. See also Dr. Frölich's book, *Die dynamoelektrische Maschinen*, Berlin, 1886.

where h is a constant of the particular electromagnet. By simple transformation this equation becomes

$$N = \bar{N} \frac{SC}{SC + h},$$

and it is clear that the meaning of h is that particular number of ampere-turns which will reduce the magnetizability to half its initial value, or will bring up the magnetism to half-saturation.

This number of ampere-turns the author named the *diacritical* number, and the number producing half-saturation he called the *diacritical* current. Dr. Frölich has independently made use of this conception, and has applied it in his formula for dynamos. The argument is his; the notation here used is, however, the author's.

This formula, though it does not take into account the difference between ascending and descending magnetizations, is quite good enough to serve as a first approximation, and is therefore useful. As pointed out by Fleming[1] and by Kennelly,[2] the justification of it is to be found in the circumstance that the reluctivity (or reciprocal of the permeability) is very nearly a simple linear function of H.

Magnetic Units.

While these pages are going through the press the Standards Committee of the British Association has proposed the adoption of a unit of magnetic flux under the name of the *weber*, equal to 10^8 magnetic lines of the C.G.S. system. The *line* is itself a unit of magnetic flux; but is too small to be convenient in many cases as a unit. But the multiples *kiloline* for one thousand lines, and *megaline* for one million lines are terms which have been found convenient by dynamo designers. One *weber* is therefore equal to 100 megalines. This magnitude has been chosen to correspond to that of the *volt* (compare p. 170); so that a wire cutting 1 weber per second will have induced in it an electromotive-force of 1 volt. The Standards Committee also proposes the name *gauss* for the C.G.S. unit of magnetic potential; being equal to $10 \div 4\pi$ of an ampere-turn. To convert ampere-turns into gausses one must multiply by $4\pi \div 10$, or by 1·257.

It should be remarked that the American Institute of Electrical Engineers has proposed the name *weber* to denote 1 line instead of 10^8 lines; and that it has proposed the name *gilbert* for the unit now called the *gauss*, while it has, unfortunately, proposed the term *gauss* as the name of a unit of flux-density to mean a density of 1 line per square centimetre.

[1] *Journ. Inst. Elec. Engineers*, xv. 570, 1886.
[2] *Electrical World*, xvii. 358, 1891.

CHAPTER VII.

THE MAGNETIC CIRCUIT.

KNOWING the magnetic properties of the materials with which we have to deal, we are in a position to calculate the number of ampere-turns necessary to produce the desired flux in the magnetic circuit of a dynamo of any given shape and dimensions. The magnetomotive-force M, which is equal to 1·257 times the ampere-turns C S, depends upon the reluctance R of the circuit, and the amount of flux N required. We in fact have the general equation

$$M = N R.$$

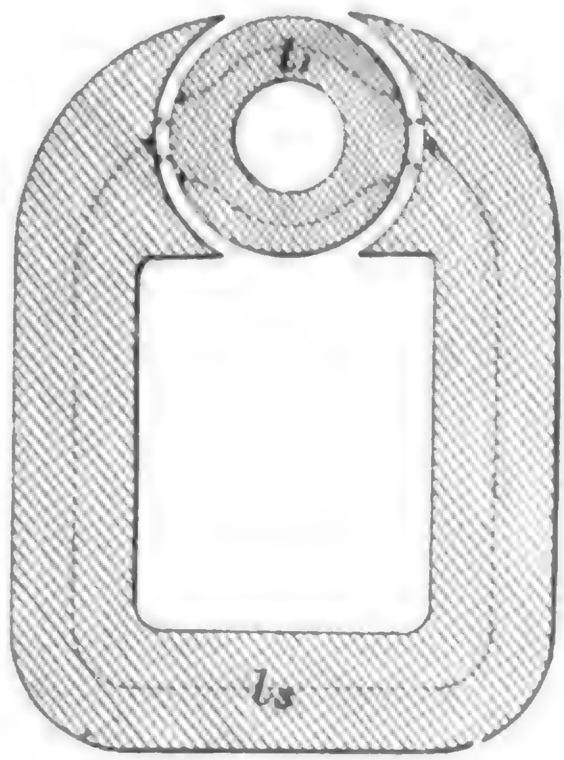


FIG. 93.

But as the total reluctance is made up of the reluctances of various parts of the circuit in series with one another, and which do not necessarily carry the same amount of flux, it is convenient to consider the parts separately. Referring to Fig. 93, which gives a diagrammatic view of the magnetic circuit of a bipolar dynamo, we have three parts, namely an iron armature-core, the two air-gaps, and the iron field-magnets.

If the average length[1] of the path for the magnetic lines in the armature core is denoted by l_1 and the average sectional

[1] For an example in the estimation of these lengths and areas see p. 355.

area by A_1 and the permeability by μ_1, the reluctance of the core will (see p. 119) be $\frac{l_1}{\mu_1 A_1}$. The total flux N through the armature divided by A_1 gives the flux-density B, so that μ_1 can be ascertained from the permeability curve of the material used. Then $\frac{N l_1}{\mu_1 A_1}$ gives the magnetomotive-force required to drive the flux through the armature core. Similarly $\frac{2 N l_2}{A_2}$ (where l_2 and A_2 are the length and area respectively of one of the air-gaps) gives the magnetomotive-force required to drive the flux through the two air-gaps. The flux through the field-magnets is greater than that through the armature, owing to magnetic leakage. As will be seen below we are able to express the average flux through the field-magnet in the form v N, where v is a number (generally about 1·3) which can be ascertained from the shape of the magnet (see p. 151). Having found the permeability μ_3 of the material of the field-magnet when carrying the flux v N through the area A_3, we can write $\frac{v N l_3}{\mu_3 A_3}$ for the magnetomotive-force required for this part of the circuit. Then the total ampere-turns required will be

$$S\,C = \frac{M}{1\cdot 257} = \frac{N}{1\cdot 257}\left\{\frac{l_1}{\mu_1 A_1} + \frac{2 l_2}{A_2} + \frac{v l_3}{\mu_3 A_3}\right\}.$$

This method of calculation is substantially that proposed independently in 1886 by Drs. J. and E. Hopkinson, and by Mr. Kapp. But the Hopkinsons went much further in their investigation. They plotted a separate curve for the relation between the magnetomotive-force and the flux for each separate part of the magnetic circuit, and then summed up the separate curves so as to obtain a final resultant characteristic curve. This is done first on the assumption that there is no magnetic leakage; and after a first approximation has thus been obtained, the theoretical result is compared with the actual result of experiment, thereby affording a means of estimating the corrections that must be introduced.

As a matter of fact, the Hopkinsons stated their formula a little more generally. Instead of assuming the existence of μ for the different parts, they contented themselves with saying that the flux-density in each part must be some function of the magnetic force acting in that part. Now, if there be a flux of N magnetic lines passing through area A square centimetres, the flux-density B will be equal to N/A. Accordingly, we may write for the magnetomotive-force acting in the armature part of the magnetic circuit $f\left(\frac{N}{A_1}\right) \times l_1$, which "function" may be examined and plotted out as a curve. In fact the curves of magnetization, such as are given on p. 123, are nothing else than curves which show the relation between the magnetizing forces and the amount of magnetism they induce. There will be a similar expression $f\left(\frac{N}{A_3}\right) \times l_3$ for the magnetomotive-force that acts in the field-magnet part, whilst for the gaps the magnetomotive-force is simply $\frac{N}{A_2} \times 2\,l_2$; for the function for air = 1. The whole or integral magnetizing force will be got by adding together the separate terms

$$l_1 f\left(\frac{N}{A_1}\right) + 2\,l_2 \frac{N}{A_2} + l_3 f\left(\frac{N}{A_3}\right) = 4\,\pi\,S\,C \div 10.$$

This mode of stating the matter has the following advantages:—(1) The use of the function of which the value is to be found by reference to a curve or tabulated set of observations (such as those given in the preceding chapters, instead of merely using the symbol μ, makes the expression more general; (2) the separate terms being differently affected by leakage of the magnetic lines, it is easy to apply corrections separately.

If then we plot out, separately, curves for each of the three terms, so as to show separately the numbers of ampere-turns required to drive different amounts of magnetic flux through each of the separate parts of the circuit, we may then combine them in a resultant curve. Having in this way built

up a curve characteristic of the magnetization, the Hopkinsons then proceeded to correct it by considering the leakage. They found that in the dynamo experimented upon (an Edison-Hopkinson) only about three-fourths of the magnetic lines created in the field-magnet actually passed through the armature-core, the rest leaking across either between the pole-pieces through the air or the bed-plate, or else turning back from the pole-pieces, to the yoke at the top. Experiment gave the ratio of the magnetic flux at a point half-way up the upright iron cores to the flux through the armature as 1·32. Let the symbol v stand[1] for this ratio. Then in the particular dynamo experimented on there was a yoke at the top through which the length of (curved) path was l_4, and which had cross-section A_4. There were also solid pole-pieces, for which the corresponding quantities were called l_5 and A_5. Inserting these additional matters into the equation, it now becomes

$$l_1 f\left(\frac{N}{A_1}\right) + 2\, l_2 \frac{N}{A_2} + l_3 f\left(\frac{v\,N}{A_3}\right) + l_4 f\left(\frac{v\,N}{A_4}\right) + 2\, l_5 f\left(\frac{N}{A_5}\right)$$
$$= 4\,\pi\, S\, C \div 10.$$

There are now five terms to be calculated, giving five curves (Fig. 94). Moreover, as is well known, with descending magnetizing forces the curve of magnetization is different from the curve with ascending magnetizing forces. Fig. 94, which is taken from the Hopkinsons' paper, shows how they plotted out both for ascending and descending magnetizations the five curves. Of these, A relates to the armature, B to the two interstitial gaps, C to the field-magnet cores, G to the yoke, and H to the two pole-pieces. To obtain the resultant curve the abscissæ at any particular level must be added together. For example: for a flux of 12 millions of magnetic lines, the air-gaps (curve B) required about 17,500 ampere-turns, the magnet-cores (curve C) 5000, the yoke (curve G) about 1000, and the armature (curve A) about 300, making a total of 23,800, which is accordingly plotted off to the right. The

[1] It can be determined experimentally, or calculated as hereafter shown.

resultant curve is swept through the points so calculated. The resultant ascending and descending curves are both shown. They agree remarkably well with the crosses and points which were plotted out from actual experiment. The dotted

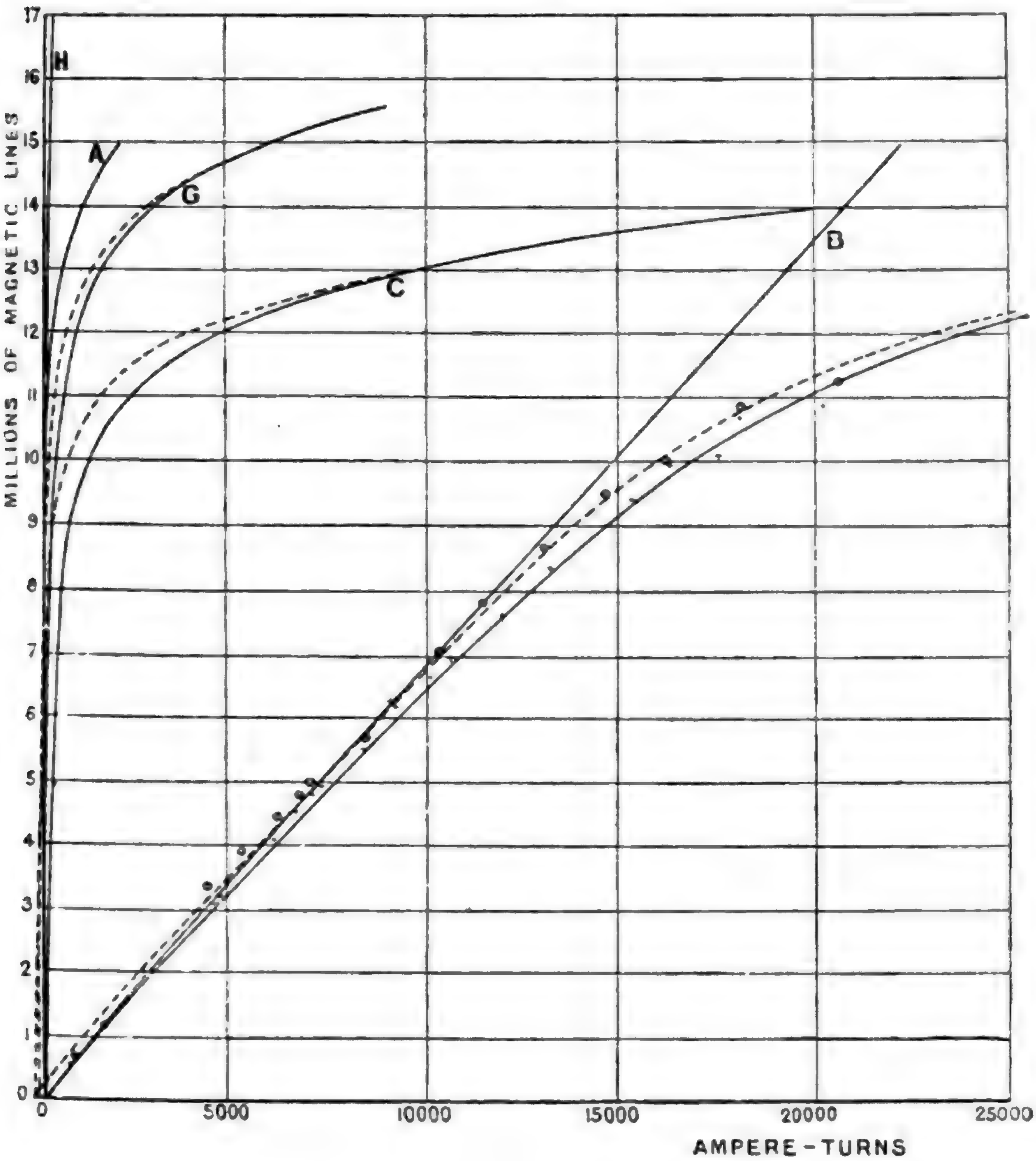


FIG. 94.

curves and the crosses surrounded with circles relate to descending magnetizations. The student should not fail to consult the original paper.

The position of the magnetizing coils on the magnetic

circuit is a matter of some importance. The electric and magnetic circuits being interlinked wherever the coils are placed they will exert the same total magnetomotive-force, but it is well, in view of the occurrence of magnetic leakage, to place the coils as near as possible to that part of the magnetic circuit where the magnetomotive-force is required. As has been pointed out above (p. 119), when there are several coils, their magnetomotive-forces will only be added together if they are interlinked with the same magnetic circuit; and therefore when a double magnetic circuit is employed (as in a dynamo of the Manchester type, for instance), each branch of the circuit requires to be wound with sufficient ampere turns to give the required difference of magnetic potential between the poles. Thus, other things being equal, twice as much power is wasted in the field-magnet. However, as the girth of each branch is less than the girth of a single circuit, it is not necessary to use quite twice as much copper in winding in order to have the same loss per coil. In cases where several magnetic circuits are required, as in a multipolar field-magnet, it is sometimes convenient to have only one magnetizing coil and interlink all the magnetic circuits with it; such an arrangement is shown in Fig. 425. It would even be possible to wind the magnetic circuit several times round the electric circuit.

Leakage of Magnetic Lines.

Whenever there exists a difference of magnetic potential between two points, a certain number of magnetic lines will pass from one to the other, whatever the medium between them may be. Thus, with a dynamo field-magnet between the poles of which it is necessary to maintain a high difference of magnetic potential a large number of lines will pass through the air from pole to pole, instead of going through the armature, leaking out sideways and constituting a *stray field.*

It should be borne in mind that magnetic leakage from the field-magnet of a dynamo does not cause any waste of energy except in so far as it necessitates a larger number of ampere

turns by increasing the flux-density, and therefore the drop in magnetic potential in the magnet core. In those cases where the reluctance of the iron core is very small as compared with other parts of the magnetic circuit, leakage does no harm. In field-magnets of alternators of the type shown in Figs. 377 and 425 the leakage is enormous, but it is of no consequence so long as the requisite difference of magnetic potential can be maintained between the poles without an undue expenditure of exciting current.

The ratio of total field to useful field is known as the *coefficient of leakage* and denoted by symbol v. The following are its values in sundry types of machines.

STRAY FIELD IN DIFFERENT DYNAMOS.

Name of Machine.	Field.	Armature.	Remarks.	Value of v.
Edison-Hopkinson	Bipolar	Drum	Poles next bed-plate	1·32
Edison (American)	Bipolar	Drum	Poles next bed-plate	1·4
General Electric Co.	Multipolar	Drum	Direct-driven	1·25
Kapp	Bipolar	Drum	Yoke next bed-plate	1·30
Siemens	Bipolar	Drum	Yoke next bed-plate	1·30
Manchester	Double Magnet, 2-pole	Long Ring	Bed and one pole cast together	1·49
Ferranti	Double Magnet, multipolar	Coreless Disk	Ordinary pattern (alternating)	2·00

In a series of machines of any given type, the leakage factor is less in the larger sizes. For instance, in the bipolar Edison dynamos it varies from 2·0 in the 100-watt machine to 1·20 in the 300 kilowatt machine. In large multipolar machines, with inward-pointing poles, the coefficient varies from 1·5 in a 2-kilowatt 4-pole machine to 1·15 in a 2000-kilowatt machine.

The stray field around a dynamo may be explored by moving a compass-needle about in it. A method of ex-

ploring the effect in the neighbourhood of dynamos has been perfected by Messrs. Edser and Stansfield.[1] They found that the stray field immediately behind one of the poles of a Kapp bipolar dynamo had a value of about 300 C.G.S. units. At a distance of 5 inches away along a horizontal line at right angles to the shaft, it had fallen to 160, at 10 inches to 80, at 20 inches to 22, and at 30 inches to 5 units. Fig. 95 depicts the general direction of the magnetic lines that leak from an Edison-Hopkinson dynamo. It will be noted that leakage takes place in other ways than from pole to pole. There is a tendency for magnetic lines to leak from the pole-pieces to the yoke at the top. The cast-iron bed-plate being in proximity to the two poles (where the difference of magnetic potential is greatest) promotes leakage through itself, even though the machine is mounted on a zinc footstep.

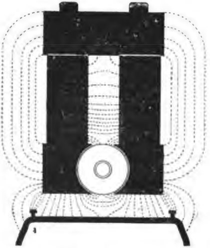


FIG. 95.—STRAY FIELD OF AN EDISON-HOPKINSON DYNAMO.

Many machines have been examined as to their magnetic leakage by Carl Hering,[2] who also has given drawings of

---

[1] *Electrician*, xxix. 118, June 3, 1892.

[2] *Electrical Review*, xxi. 186 and 205, 1887.

them. An extraordinary case was found to be afforded by the stray field of the Thomson-Houston arc lighting dynamo (Fig. 311). The reader should also refer to some experiments by Carhart,[1] and to others by Trotter,[2] Wedding,[3] Puffer,[4] Mavor,[5] and Wiener.[6]

It is evident that the leakage coefficient cannot be constant in a given machine, for the amount of leakage depends on the relative permeance of the path through the armature core and of the stray paths outside. Now the permeability of air is a constant, whilst that of the iron cores decreases as the degree of saturation is raised; so that the leakage increases with higher excitation. Also when a large current is drawn from the armature, the demagnetizing reaction of the armature current directly promotes leakage, as it raises an opposing magnetomotive-force in the direct path of the magnetic lines. Moreover, since leakage takes place more or less all over a magnet, it is clear that what we call the coefficient of leakage is only a sort of average.

By experiment we may determine the actual value of the leakage ratio in various parts. Drs. J. and E. Hopkinson did this for a "Manchester" dynamo,[7] using exploring cells placed around the field-magnet of the dynamo in various positions. The number of magnetic lines which were thus enclosed was ascertained by suddenly cutting off the exciting current and noticing the resulting induction current in a suitable galvanometer. A still more complete examination was made by Lahmeyer[8] on an iron-clad dynamo (Fig. 96). In this case six separate exploring coils, each having the same number of turns, were used. That surrounding the armature, enclosing the useful field, is called A, the others being numbered. The

[1] *Electrical Review*, xxv. 286; and *Electrician*, xxiii. 644, 1889.

[2] *Journal Inst. Electrical Engineers*, xix. 243, 1890.

[3] *Elektrotechnische Zeitschrift*, xiii. 67, 1892.

[4] *Electrical Review*, xxx. 487, 1892.

[5] *Electrical Engineer*, xiii. 428, 1894. "New Points in Dynamo Design."

[6] *Electrical World*, xxiv. 647, Dec. 22, 1894.

[7] See their paper in *Phil. Trans.*, Part i. 331, 1886; and *Electrician*, xviii. 39, 63, 86 and 175, Nov. and Dec. 1886.

[8] *Elektrotechnische Zeitschrift*, ix. 283, 1887.

deflexions obtained are given in column 2 of the following table. The maximum flux was found at 3. Taking this number as 100, the percentages of leakage at the coils are given in column 3. In column 4 are given the various fluxes, taking that through A as 100, and in column 5 the values of v at the various parts. It is clear that the yoke parts were of insufficient thickness.

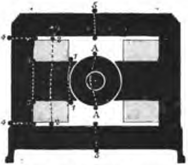


FIG. 96.—EXPLORING THE MAGNETIC LEAKAGE OF A DYNAMO.

A	780	10·9	100	1
I.	788·5	10·1	101	1·01
II.	861	1·6	110	1·10
III.	876	0	112	1·12
IV.	850	3·0	109	1·09
V.	749	14·5	96	0·96

In the case of the Edison-Hopkinson dynamo, the Hopkinsons give 1·32 for v, this being the ratio observed between the throw when the exploring coil was placed half-way up the magnet limbs and when it was placed around the armature. If the exploring coil had been placed higher up, and if the armature had been excited so as to exert a demagnetizing action, the leakage coefficient would have been found to be at least 1·4.

CALCULATION OF LEAKAGES.

It is possible to predetermine, from the working-drawings of a dynamo before it is built, the probable amount of leakage. Calculations of the leakage are based upon the principle that where a circuit offers alternative paths, the magnetic flux will divide itself between the paths in the proportion of their relative facility for flow, exactly as an electric current divides where there are alternative conducting paths. In fact, the law of shunts has been found to hold good for magnetic lines. The reader should consult the researches of Ayrton and Perry[1] on this point. It follows that along any branched path the joint *permeance*[2] (or magnetic conductance) will be the sum of the permeances of the separate paths. Hence, if the permeances of the separate paths of the useful and waste magnetic fluxes of a dynamo are known, the coefficient of allowance for leakage, v, can be calculated, it being the ratio of the total flux to the useful flux. Call the useful flux u and the waste flux w; then

$$v = \frac{u + w}{u}.$$

But each of these is a complicated quantity; therefore the more complete formula is

$$v = \frac{u_1 + u_2 + u_3 + \quad . \quad . \quad . \quad . \quad + w_1 + w_2 + w_3 + \quad . \quad . \quad .}{u_1 + u_2 + u_3 + \quad . \quad . \quad . \quad .}$$

In order to determine the separate permeances along the various leakage paths, we must resort to some useful rules or lemmas originally suggested by Professor Forbes,[3] which consist in certain approximate integrations. For the convenience of British engineers the values have been recalculated into inch measures instead of centimetre measures.

[1] *Journ. Soc. Teleg. Engineers and Electricians*, 530, 1886.

[2] *Permeance* is of course the reciprocal of magnetic reluctance; just as electricity conductance is the reciprocal of electric resistance.

[3] *Journ. Soc. Teleg. Engineers*, xv. 551, 1886.

Rule I.—Permeance between two parallel areas facing one another. Assume (Fig. 97) that the magnetic lines are straight and equally distributed over the surfaces: then,

Permeance $= 3{\cdot}1918 \times$ mean area (square inches) $\div$ distance (inches) between them

$$= 1{\cdot}596 \times (A_1'' + A_2'') \div d''.$$

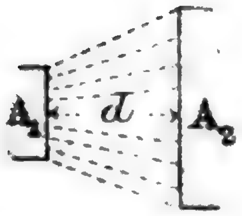


FIG. 97.

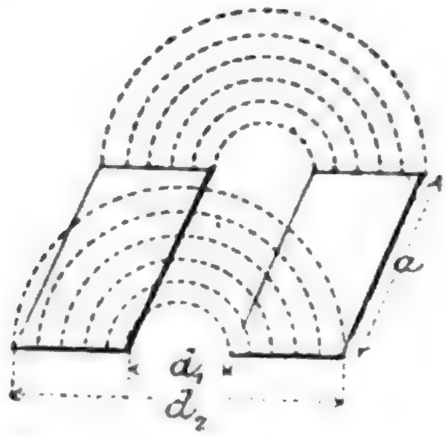


FIG. 98.

Rule II.—Permeance between two equal adjacent rectangular areas lying in one plane. Assuming (Fig. 98) lines of leakage to be semicircles, and that distances d_1'' and d_2'' between their nearest and furthest edges respectively are given; also a'' their width along the parallel edge:—

$$\text{Permeance} = 2{\cdot}274 \times a'' \times \log_{10} \frac{d_2'}{d_1''}.$$

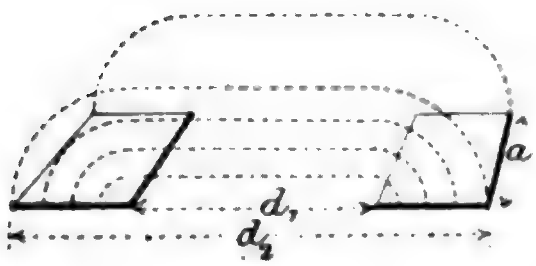


FIG. 99.

Rule III.—Permeance between two equal parallel rectangular areas lying in one plane at some distance apart. Assume (Fig. 99) lines of leakage to be quadrants joined by straight lines.

$$\text{Permeance} = 2{\cdot}274 \times a'' \times \log_{10}\left\{1 + \frac{\pi(d_2'' - d_1'')}{d_1''}\right\}.$$

Rule IV.—Permeance between two equal areas at right-angles to one another.

Permeance = double the respective values calculated by II.

If measures are given in centimetres these rules become the following:—

I. $\frac{1}{2}(A_1 + A_2) \div d.$

II. $\frac{a}{\pi}$ hyp. log $\frac{d_2}{d_1}$.

III. $\frac{a}{\pi}$ hyp. log $\left(1 + \frac{\pi(d_2 - d_1)}{d_1}\right)$.

Using these rules to predetermine the leakage to fly-wheels, pedestals and shafts, it is possible from the working drawings to predict the performance of a machine to within 2 per cent.

The author has given (in his work on *The Electromagnet*) some further rules, including the case of leakage between two parallel cylindrical limbs.

In the fourth edition of the present work an example of the application of these rules to the calculation of the leakage of an actual dynamo was given in great detail.

CHAPTER VIII.

FORMS OF FIELD-MAGNETS.

WITH the principle of the magnetic circuit to guide him, the reader will have little difficulty in judging of the relative value of the various designs of field-magnets; for he will remember that the magnetic circuit of highest permeability will have the most compact form, greatest cross-section, softest iron, and fewest joints. In many cases, however, the structure which acts as magnet has also to do duty as a framework, involving other considerations. Theoretically it is better that the field-magnet of a simple 2-pole machine should be constituted of a single magnetic circuit than of two (see p. 150); though for practical structural reasons the double circuit is preferable in some cases. A double circuit, that is to say one resembling No. 3 or No. 8 of the accompanying Fig. 100, has in general the advantages that it affords a more stable framework, and that its magnetic field is less liable to distortion than that of No. 2. These points should be borne in mind in considering the forms depicted in the accompanying figures. No. 1 of these illustrations shows the form adopted by Wilde for use with the shuttle-wound armature of Siemens. Two slabs of iron are connected at the top by a yoke, and are bolted below to two massive pole-pieces. There are four joints in the magnetic circuit in addition to the armature gaps, and the yoke is insufficient. No. 2 shows the form adopted in the Edison dynamos (standard bipolar pattern). The upright cores are stout cylinders. The yoke is of immense thickness; the pole pieces are massive, but their lower corners are cut away. There are as many joints as in Wilde's form; but such a circuit should possess a far higher magnetic conductivity than Wilde's, owing to the greater cross section.

One difficulty with such single circuit forms is how to mount them upon a suitable bed-plate. If mounted on a bed-plate

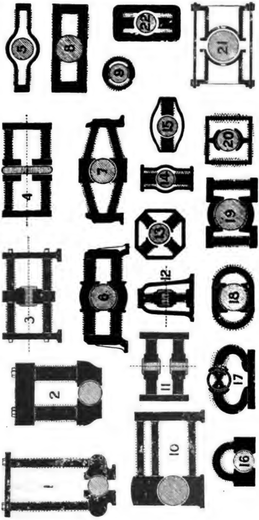


FIG. 100.—TYPICAL FORMS OF FIELD-MAGNETS.

of iron, a considerable fraction of the magnetism will be short-circuited away from the armature, as has been shown in the

preceding chapter. In the larger form, No. 10, used at one time by Edison, this difficulty was only partially obviated by turning the magnets on one side.

A favourite type of field-magnet, having a double magnetic circuit with "consequent" poles, is represented in No. 3; it was introduced by Gramme. It may be looked upon as the combination of two such forms as No. 1, with common pole-pieces. Nos. 3 to 9 may be looked upon as modifications of a single fundamental idea. No. 4 gives the form used in the Brush dynamo (plan), the two magnetic circuits converging upon the ring armature. The diagram will serve equally for many forms of flat-ring machine; but in most of these the poles at the two flanks of the ring are joined by a common hollow pole-piece, embracing a portion of the periphery of the ring. No. 5 shows an early form of Siemens, with arched ribs of wrought iron, having consequent poles at the arch. The circuit is here of insufficient cross section. No. 6 depicts a form adopted by Weston: and very similar forms have been used by Crompton, and by Paterson and Cooper. There is a better cross-section here. No. 7 is a form used by Bürgin and Crompton, and differs but slightly from the last. It has one advantage—that the number of joints in the circuit is reduced. No. 8 is a form used by Crompton, Kapp and others. No. 9 is the form adopted in the little Griscom motor. No. 18 is a further modification due to Kapp. No. 19, which also has consequent poles, was used by McTighe, by Joel, and by Hopkinson ("Manchester" dynamo), by Clark, Muirhead & Co. ("Westminster" dynamo), by C. E. L. Brown (Oerlikon), and in some of Sprague's motors; but with slight differences in proportions of the details. The main difference between No. 19 and No. 6 lies in the position selected for placing the coils, No. 19 requiring two, No. 6 four. No. 20, which is a design of Elwell and Parker, is a further modification of No. 3, and would be improved by having a greater cross-section. In No. 3 (Gramme), it is usual to cast the pole-pieces and end-plates, but to use wrought iron for the longitudinal cores. The requisite polar surface must be got by some means, and when the core was made thin, the two courses

open were either to fasten upon the core a massive pole-piece (Nos. 1, 3, 4, 6, 7, 19, 20), or else to arch the core No. 5 so that its lateral surface was available as a pole. Now, however, that it is known that massive cores are of advantage, the requisite polar surface can be obtained without adding any polar expansion or "piece," but by merely shaping the core to the requisite form (No. 8). This must not be regarded as a thinning of the magnet; for though mere reduction of cross-section at any part of the circuit would reduce the magnetic conductivity, reduction of the thickness for the purpose of bringing the armature more closely into the circuit will have quite the opposite effect. In fact the horizontal bars above and below the armature might be thinned away to nothing at their middle point, but for structural reasons. In all such forms of double magnetic circuit each half of the field-magnet may be regarded as having to furnish magnetic lines to its own half of the armature. Nos. 11 to 15 illustrate forms of field-magnet having *salient*, as distinguished from *consequent* poles. No. 11 is a double Gramme machine designed by Deprez. Nos. 12 and 13 are two of the innumerable patterns due to Gramme himself. These are both of cast iron; and it will be noticed that in No. 13 there are no joints, it being cast in one piece. No. 14 is a form used by Hochhausen, and is practically identical with 21, save in the position of the axis of rotation. The iron flanks of No. 14 tend to produce a certain short-circuiting of the magnetism by their proximity to the poles; and their sectional area is insufficient. No. 15, used by Van de Poele, is similar. No. 16 is the form used by the author in small motors, and is cast in one piece. The semicircular form adopted for the core was intended to reduce the magnetic circuit to a minimum length. No. 17 has salient poles reinforced by other electro-magnets within the armature. No. 21 shows in section the double tubular magnets of the Thomson-Houston dynamo, the spherical armature being placed, as in Nos. 12, 14 and 15, between two salient poles. There is a curious analogy between Nos. 21 and 19; but they entirely differ in the position of the coils. No. 22 is a design by Kapp, in which there are two salient poles

of similar polarity, and two consequent poles between them, one pair of coils sufficing to magnetize the whole quadruple circuit. Almost identical forms have been employed by Rankine Kennedy ("iron-clad" dynamo), No. 25. Lahmeyer and Wenström employ iron-clad forms resembling No. 15. That of Wenström has for its yoke an external iron cylinder. No. 23, Fig. 101, with armature at the top, is known as the "over-type" of bipolar machines. It is an old form which was revived in 1884 by Gramme ("type supérieur"), by Kapp, by Siemens and by others. No. 24 is Brown's very massive form. No. 26 is designed by Prof. George Forbes. The ironwork is in two halves; the coils, which are entirely enclosed, are so placed as to magnetize the armature directly, one coil occupying all the available space between the field-magnet and the upper half of the armature; the other the similar space around the lower half. No. 27 is a 4-pole form

FIG. 101.—TYPICAL FORMS OF FIELD-MAGNETS.

adopted by Elwell-Parker, and also by Crompton. No. 28 is a multipolar form, used by Wilde, Gramme and others, the poles which surround the ring being alternately of opposite sign. It is now largely used for alternate-current machines such as those of Westinghouse, Mather and Platt (Hopkinson), and others. In No. 22, a modification of this design by Thury, for use with a drum armature, the six inwardly-directed poles are magnetized by coils wound upon the external hexagonal frame. No. 30 is a sketch of a form introduced by Siemens and Halske, and also by Ganz, Fein and others, wherein an external ring rotates outside a very compact and substantial 4-pole electro-magnet. Similar machines, but with more than four internal poles, are largely used in Germany, for large central-station machines.

FIGS. 102, 103.—TYPICAL FORMS OF FIELD-MAGNETS.

Another form of field-magnet is shown in No. 31. This, which is a single horse-shoe with but one coil upon it, was a design by the author of this work early in 1886: it has been used largely by Goolden and Co., by Greenwood and Batley, and other British makers. No. 32 represents also a machine requiring but one coil, and is of the iron-clad type. It was devised by McTighe in 1882, and has been revived by Stafford and Eaves. A pattern designed by Mordey for the Brush Company resembles No. 32, but has an external iron cylinder to enclose the coil. In Fig. 96 is represented Lahmeyer's form, also with inward-pointing poles: like the preceding it belongs to the "iron-clad" type, the yoke of the magnet being exterio

Eickemeyer's dynamo (Fig. 104) realizes the suggestion of Forbes to place the magnetizing coils over the armature. The coils, which are separately wound on formers, fit into recesses between the upper and lower yokes and the inwardly projecting polar masses. Fig. 105 gives a view showing the interior disposition when one of the polar masses is removed. The defect of such forms is the difficulty of ventilating the closely enclosed armature.

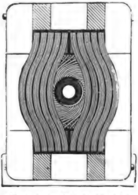


FIG. 104.—EICKEMEYER'S DYNAMO.

A typical form for alternate-current machines is that introduced by Wilde, and used by Siemens, Ferranti and others, having two crowns of alternate poles facing one another.

Fig. 107 represents a form of 4-pole field-magnet used by the Brush Company for their Victoria (Mordey) machines, having double magnetic circuits

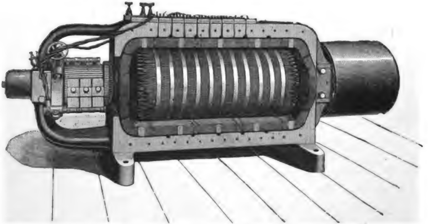


FIG. 105.—EICKEMEYER'S DYNAMO, WITH MAGNETIZING COILS SURROUNDING ARMATURE.

and consequent poles. The cores to receive the coils are of wrought iron, whilst the end frames and pole-pieces are cast.

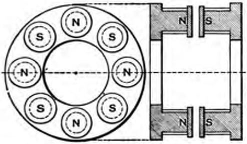


FIG. 106.—TYPICAL ALTERNATE-CURRENT FIELD-MAGNET.

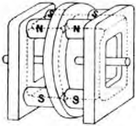


FIG. 107.—FOUR-POLE MAGNET (MORDEY).

This should be contrasted with the form of 4-pole magnet, Fig. 108, designed in 1888 by Brown, and constructed by the

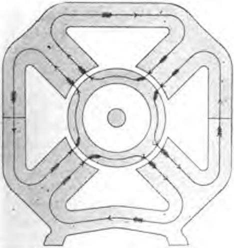


FIG. 108.—FOUR-POLE MAGNET (BROWN).

Oerlikon works, for some large 300 horse-power machines for transmission of power. These are made entirely of cast iron,

and have salient poles. The direction of the flux through these machines is indicated by dotted lines.

The most notable departure in the forms of field-magnets in recent years is that due to Mordey, in whose alternator there is a field-magnet (see Fig. 419 and Plate XIV.), which, though it possesses but a single magnetic circuit with one exciting coil upon it, is nevertheless multipolar. This result is attained by the use of multiple pole-pieces which subdivide the magnetic flux into a number of separate magnetic fields. The field-magnet of the three-phase alternator (Figs. 422 and 425), designed by Brown for the transmission of power from Lauffen to Frankfort, is also of this improved kind, with a single exciting coil. In many recent machines a similar simplification is to be found.

Among such a multiplicity of designs one seeks for some indication as to the best. But the best for one purpose is not the best for all. Some designs are suitable for cast iron; others for wrought iron; others again, such as Figs. 102 and 107, are expressly intended to be composite, having wrought cores for the bobbins and cast polar masses. It is desirable, where possible, to have the core upon which the coils are wound cylindrical, as that shape has the least perimeter for a given sectional area, and in consequence allows a saving in copper wire as well as making the winding simpler. Of course cylindrical cores are not suitable for machines with long drum armatures. There is a tendency at the present time to make the wound core of a material of high permeability, so that its perimeter can be reduced and a saving effected both in iron and copper. As the exciting coils are generally wound on detachable reels, the shape of the field-magnet should permit of these being put off and on. For small machines a simple circuit is probably the best. For large machines it is found needful to multiply the number of poles: and for alternators, multipolar forms are necessary for obtaining a sufficiently frequent alternation of currents.

Probably the future will see a general simplification of multipolar forms by the adoption of branched magnetic circuits.

In calculating those forms which have double or multiple

magnetic circuits, it is usual to simplify matters by considering one element of the whole, and making the calculations for it. Thus, for example, in Fig. 109, which depicts the half of such a machine as No. 8 of Fig. 100, it is sufficient to calculate the magnetic reluctances of half the machine in order to ascertain the number of ampere-turns that must be wound upon it; a similar number being wound upon the other half. Forms with a double magnetic circuit are preferable to those, such as Nos. 2, 23, and 31, with a single magnetic circuit, in all cases where there is likely to be much armature reaction. For in such forms as No. 23 the field is weaker under the two upper pole-tips than between the two lower ends of the pole-faces: in consequence, there is a powerful attraction downward of the armature. Further, because of this inequality of field the cross-magnetizing force of the armature will produce, in the single-magnet forms, an unsymmetrical distortion. As a consequence there is sure to be sparking at the brushes. For large-load bipolar armatures it is advisable not only to use double-magnets, but to separate their two halves by a distance-piece of brass.

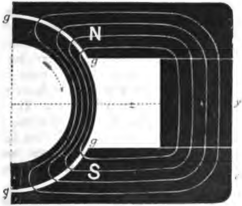


FIG. 109.—HALF OF A DOUBLE MAGNETIC CIRCUIT MACHINE.

CHAPTER IX.

ELEMENTARY THEORY OF THE DYNAMO. MAGNETO, AND SEPARATELY-EXCITED MACHINES. SERIES MACHINES. SHUNT MACHINES.

EXPERIENCE has shown that the main problems that require to be considered in the design of dynamos, are best solved by reference to the *magnetic circuit of the machine as a whole*, the iron core inside the armature being regarded as a constituent part of that circuit. In all that follows the armature is regarded merely as consisting of a certain number Z of conductors, grouped in a particular way around an axis of rotation, their function being to cut across the magnetic lines that are furnished by the magnetic circuit. The symbol **N** stands for the *magnetic flux*, which, in the case of bipolar machines, is *the whole number of magnetic lines that traverse the armature*, entering it on one side and again leaving it on the other. For multipolar machines, **N** stands for the flux from one pole that traverses the armature.

The number of revolutions *per second* made by the armature is denoted by the symbol n. It is found that the average electromotive-force generated by the armature is simply proportional to each of these quantities, so that by taking the appropriate units we may write, as will presently be seen, as the fundamental equation

$$\text{(average) } E = n\,Z\,\mathbf{N} \quad . \quad . \quad . \quad . \quad . \quad [\text{I.}]$$

In the present chapter an expression is first found for the average electromotive-force, which expression serves as the fundamental equation of all dynamos. Then by introducing appropriate formulæ for the various circuits, equations are deduced for the various kinds of series-wound, shunt-wound and compound-wound dynamos.

Symbols Used.

It may be well to point out that in this and the succeeding chapters the following symbols are used in the following significations :—

A	area, expressed in *square centimetres.*	
B	the flux-density, or number of magnetic lines per square centimetre.	
b	number of external wires in a section of the armature. In speaking of alternators b stands for the "breadth coefficient" (see Chap. XXIII.).	
β	angular breadth of a section of armature coil or of segment of collector.	
C	current in external circuit,	expressed in *amperes.*
C_a	current in armature,	
C_m	current in series coil or main circuit,	
C_s	current in shunt coil,	
c	number of segments of collector or commutator.	
E	entire electromotive-force generated in an armature,	expressed in *volts.*
e	difference of potential from terminal to terminal,	
$\mathcal{E}$	electromotive-force of some external supply of electricity,	
η	economic coefficient, or efficiency (see pp. 107 and 187, and Chap. XXX.).	
F	force (i. e. push or pull), expressed in either *dynes*, *poundals*, *grammes'* weight or *pounds'* weight.	
H	intensity of magnetic field (lines per sq. centim. *in air*).	
L	coefficient of self-induction.	
λ	average length of one turn of wire ; also used for angle of lead.	
μ	magnetic permeability of iron.	
N	the magnetic flux, or whole number of magnetic lines that traverse a magnetic circuit.	
n	number of revolutions *per second.* In alternate-current problems n = the frequency.	
ω	angular velocity (expressed in *radians*-per-second).	
p	number of *pairs* of poles. In alternate-current problems the symbol p is used for the *pulsation*, $p = 2 \pi n$.	
R	resistance of external circuit,	expressed in *ohms.*
r_a	resistance of armature coils,	
r_s	resistance of shunt coils,	
r_m	resistance of series coil on field-magnets,	
r	internal resistance of dynamo ; equal to $r_a + r^m$ or to $r^a + r^s$ according to circumstances,	
ρ	resistance per unit of length,	
S	number of spirals or turns of wire in coil.	

S_m number of turns in a coil in the main circuit, in series with armature.

S_s number of turns in a coil in shunt.

T torque, or turning moment, or angular force, or couple, expressed in *dyne-centimetres*, *gramme-centimetres*, *metre-kilogrammes*, or *pound-feet*, according to circumstances.

T is also used in the section on alternate currents for the periodic time of the alternating current, measured in *seconds*.

t time measured in *seconds*.

v coefficient of allowance for magnetic leakage.

V volts at terminals of dynamo or motor.

W } w } activity, or power, or work-per-second, expressed in *watts* or in *horse-power*.

Z number of conductors on armature, counted all round the periphery.

ϕ angle of phase difference between alternating currents or electromotive-forces.

Wherever inch units are used instead of centimetre units, the marks used on p. 104 will be employed for distinction.

Fundamental Equation of Dynamo.

To find the average electromotive-force of a moving conductor, we must remember that, by definition, see p. 22, this is (in absolute C.G.S. units) numerically equal to the number of magnetic lines that are cut in one second by the conductor. Also the practical unit, the *volt* being by definition equal to 10^8 absolute C.G.S. units of electromotive-force; it will be necessary to divide the number of C.G.S. units by 10^8 in order to reduce the number to volts. Further, when there are, as in the armatures of dynamos, a number of conductors in series with one another, the total electromotive-force of the dynamo will be equal to the sum of the electromotive-forces of those conductors that are in series with one another. The fundamental equation will then be written :—

$$\text{(average) E (in } \textit{volts}) = n \, Z \, \mathsf{N} \div 10^8 \quad . \quad . \quad . \quad . \quad . \quad [\mathrm{I}a.]$$

We will deal first with an ordinary two-pole dynamo, having an armature in which the number of "sections" is denominated by the symbol c; the number of "segments"

or "bars" in the commutator or collector will also be c. Let there be in each section b external wires or conductors, as counted on the outside of the armature core. (In ring armatures there will be the same number of external wires as there are loops or windings in the section; in drum armatures there are twice as many external wires as there are loops or windings in the section.) Then the number of external conductors or wires, reckoned all round the armature, will be $b\,c$; it will be more convenient to use the single symbol Z for this number. The number of external conductors or wires that are in series with one another electrically from brush to brush will be $\frac{b\,c}{2}$ or $\frac{1}{2}$ Z. Now let the armature rotate with a speed of n revolutions per second. (Engineers usually count the revolutions made in one minute, necessitating division by 60 to get n.) Then one revolution will take $\frac{1}{n}$ part of 1 second. We are now ready to calculate the electromotive-force.

No. of lines cut by 1 *external wire in* 1 *revolution* .. .. $= 2\,\mathrm{N}$

(because each wire cuts all the lines where they go in at one side of the armature, and where they come out on the other);

No. of lines cut by 1 *external wire in* 1 *second* $= 2\,n\,\mathrm{N}$;
No. of lines cut by $\frac{1}{2}$ Z *external wires in series in* 1 *second* .. .. $= 2\,n \times \mathrm{N}\,\frac{1}{2}\,\mathrm{Z}$;
No. of lines cut by $\frac{1}{2}$ Z *external wires in series in* 1 *second* .. .. $= n\,\mathrm{Z}\,\mathrm{N}$.
Average electromotive-force (in C.G.S. units) $= n\,\mathrm{Z}\,\mathrm{N}$;
Average electromotive-force (in *volts*) .. .. $= \frac{n\,\mathrm{Z}\,\mathrm{N}}{10^8}$ .. [I*a*.]

It will be unnecessary in every case to write the divisor 10^8 in the formula, because it is easily remembered that, if omitted for the sake of brevity, the numbers obtained can be transformed at once to volts by so dividing down.

For many purposes it is more convenient to have the fundamental equation in terms of the angular velocity. Let

the symbol ω represent the angular velocity. Then $\omega = 2\pi n$; for, in each revolution, the angle described is 2π *radians* or 360 *degrees.* Consequently $n = \omega / 2\pi$, which gives;

$$(\text{Average})\ E = \frac{\omega}{2\pi} Z N \quad . \ . \ . \ . \ . \ . \ . \ . \quad [1b.]$$

It will be observed that this electromotive-force is simply an average; and it depends on the construction of the armature how much fluctuation there is in the value during a rotation.

If, as in Fig. 110, the armature had but two external conductors forming a simple loop, then the electromotive-force would fluctuate between zero and a maximum. Calling the lowest point of the rotating loop in its vertical position 0°, then the position on the left of the dotted line will be 90°, if we reckon the rotation in the clockwise direction. The top point will be 180°, and the point on the extreme right 270°. Then the induced electromotive-force will be zero as the coil passes through 0° and 180° (for at the positions 0° and 180° the conductors will be sliding along, rather than cutting, the magnetic lines), and a maximum as the coil passes through 90° and 270°. The *rate* of enclosing or "cutting" will be a *maximum* when the *actual number* of lines enclosed is a *minimum*, and *vice versâ.* (See p. 31.)

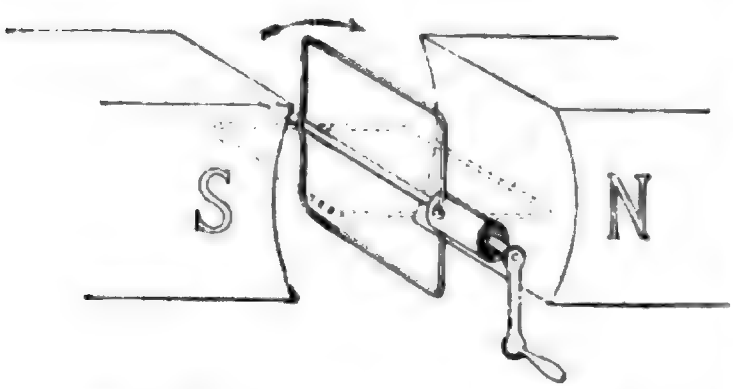


FIG. 110.—IDEAL SIMPLE DYNAMO.

At any intermediate angle, if the field is uniform, the actual number of lines of force enclosed is proportional to the cosine of the angle through which the coil has turned from its zero position, and the electromotive-force will be proportional to the sine of that angle. Strictly speaking, we ought to take the sine with a *negative* value to represent the electromotive-force, because as usually defined the induced electromotive-force is proportional to the rate of *decrease* in the number of

lines of force enclosed. We need not, however, trouble about signs, because, if the brushes are properly set at the commutator, all the induced electromotive-forces are thereby made to act in the same direction through the external circuit. The angular velocity being $2\pi n$, the angle passed through in an interval of time of t seconds will be $2\pi n t$. Calling this angle θ, and reckoning it from the lowest point as before, the electromotive-force in the loop at any time t may be calculated as follows:—The number of lines of force enclosed when the loop has turned through angle θ is $= \mathsf{N} \cos \theta = \mathsf{N} \cos 2\pi n t$; hence the rate of cutting will be $2\pi n \mathsf{N} \sin \theta$. Now, since the average value of $\sin \theta$, between the limits $\theta = 0°$ and $\theta = 90°$, is $2/\pi$, the *average* electromotive-force *per loop* may be obtained by substituting this value, giving us

$$\text{Average E per loop} = 4 n \mathsf{N}.$$

And since the number of loops that are in series between brush and brush is $\frac{1}{2}$ Z, we have finally

$$\text{(Average) E} = n \text{Z} \mathsf{N}.$$

If the coil consisted of many turns all wound in one group, like the Siemens shuttle-wound armature, p. 33, the same expressions would obviously hold good on substituting the proper number for Z.

Fluctuations of Electromotive-force.—As explained above, the actual induced electromotive-force is proportional to the sine of the angle through which the coil has turned, or

$$\text{E} = 2\pi n \mathsf{N} \sin \theta \times \tfrac{1}{2} \text{Z},$$

whence

$$\text{E} = \frac{\pi}{2} n \text{Z} \mathsf{N} \sin \theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{II.}]$$

As θ increases from 0° to 360°, the value of the sine goes from 0 to 1, then from 1 to 0, from 0 to -1 and from -1 back to 0. The values of the sine are depicted in Fig. 111. The same curve may serve then to show how the electromotive-force would fluctuate if there were no commutator. But the action of the commutator is to commute the negative inductions

into positive ones; the brushes being so arranged as to slide from one part of the commutator to the other at the moment when the inverse induction begins. This gives the curve the form of Fig. 112, which therefore represents how the voltage pulsates in the circuit of a simple old-fashioned shuttle-wound Siemens armature. Now if we could level these hills, and

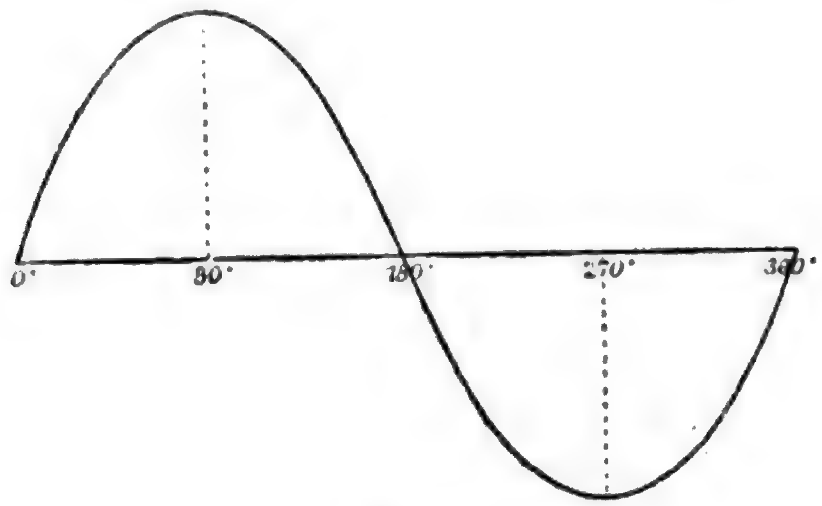


FIG. 111.

change our undulating induction into a steady one, we should get a single straight line, shown in Fig. 112 as a dotted line enclosing below it a rectangular area equal to the sum of the areas enclosed by the sinuous curves, and therefore at a height which is the average of the heights of all the points along the curves; in fact, since each sinuous curve is part of a

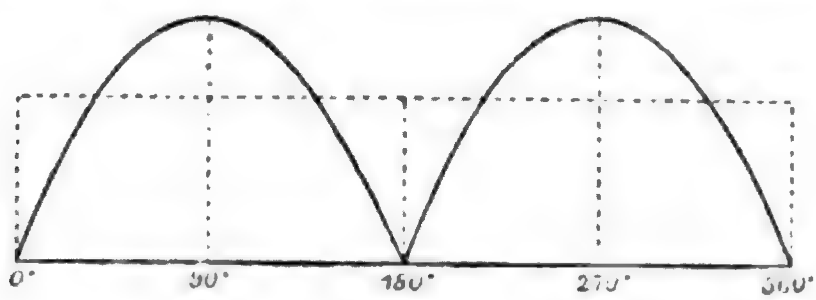


FIG. 112.

curve of sines, the *average* height will be $2 / \pi$, or about $\frac{7}{11}$ of the maximum height. In consequence of self-induction in the coils, the current will not actually fluctuate[1] as much as the voltage, the hollows being partly filled.

[1] See remarks by Cromwell F. Varley in *Phil. Mag.*, 1867, and by Puluj in *Sitzungsber. Wien. Akad.*, IIa, May 1891.

Fluctuations in a Closed-coil Armature.—As shown on pp. 39 and 60, it is, for reasons of construction, usual to wind armature coils in two sets connected in parallel. If each of the two coils consisted of 100 turns, their joint effect in inducing electromotive-force would be no greater than that of either of them separately, but the internal resistance of the armature would be halved. From this point onwards in the argument it will be assumed that the armature windings consist of *pairs* of coils. Thus, instead of one coil of 200 turns, as shown in Fig. 113, we shall take it that there is a pair of coils each of 100 turns, as in Fig. 114.

Now suppose that, in order to get a less fluctuating effect, we divide each of our original single pair of coils into two parts, and set these at right angles to one another. To take

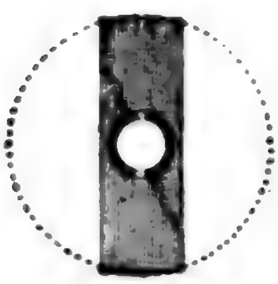


FIG. 113.

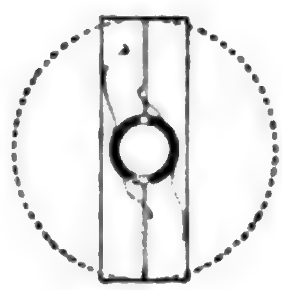


FIG. 114.

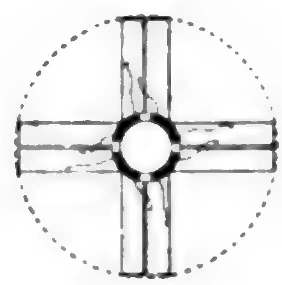


FIG. 115.

a numerical case, suppose there were originally 100 turns in each coil, and we split each into two coils of fifty turns, but set them across one another so that one comes into the best position in the field as the other is going out of it. (This arrangement is indicated in Fig. 115, which may be contrasted with Fig. 114.) In this case we shall have two sets of overlapping curves—each of them will have to be but half as high as before, because the equivalent area of each coil is only half what it was for the whole coil. Then, if there were no commutator, the induced electromotive-force in the two sets of coils would fluctuate as shown by the two curves of Fig. 116, which differ by a quarter-period from one another. But if the ends of the two "sections" of the coil are joined to a proper commutator, all the "inverse" inductions will be commuted into "direct" ones, and the two curves would

then become as in Fig. 117. The next process is to ascertain what the joint result of these overlapping electromotive-forces will be: it is evident that from 0° and 90° the two inductive actions are assisting one another, and that at 45° thay are

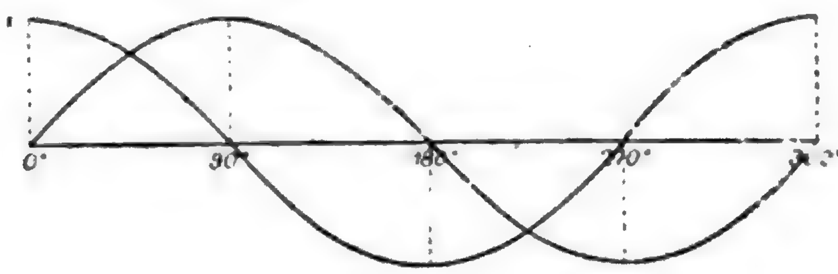


FIG. 116.

equal. The nett result here is therefore double either of them; and, in fact, the curve representing the *sum* of the two curves is given in Fig. 118. This curve shows at once a step towards *continuity*, as the fluctuations are far less than those of the

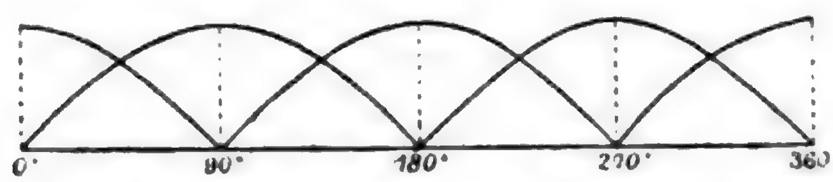


FIG. 117.

single coil, Fig. 112. If, as before, we level the undulating tops by a dotted line, we get precisely the same height as before. The *total* amount of induction (the total cutting of lines per second) is the same, and the *average* electromotive-

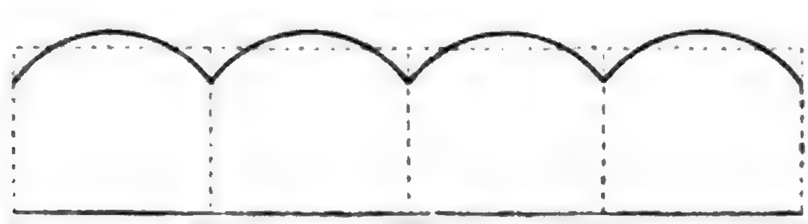


FIG. 118.

force is the same. There is no gain, then, in the total electric work resulting from rearranging the armature coils in two sets at right angles to each other; but there is a real gain in the greater continuity and smoothness of the current.

If we again split our coils and arrange them as shown in Fig. 119 at angles of 45°, in four sets of pairs of coils of twenty-five turns each, and connect them up to a proper commutator, we shall get an effect which is very easily represented by constructing two curves, each similar to the last but each of half the height, and compounding them together (Fig. 120). One of them will of course have the maximum heights of crests occurring 45° further along than those of the other curve; and when these are compounded together we get for a resultant a curve shown in Fig. 121, which has exactly the same *average* height as before, but which has still less of fluctuation. It is easily conceived that this process of dividing the coil into sections, and spacing these sections out at equal angles symmetrically, would give us a result approaching as near as we choose to an absolutely continuous

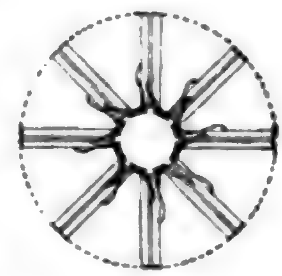


FIG. 119.

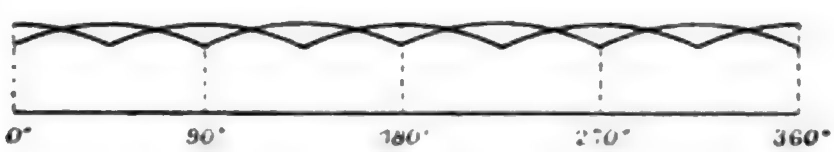


FIG. 120.

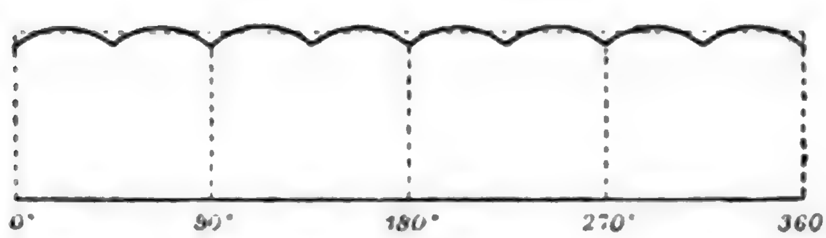


FIG. 121.

one. If our original pair of coils of 100 turns each were split into twenty sets of pairs of five turns each, or even into ten sets of pairs of ten turns each, the approach to continuity would be very nearly truly attained.

Calculation of Fluctuations.—If the variations of the electromotive-force literally followed a sine law, it would not be difficult to calculate the amount of fluctuation when a commutator with any particular number of segments is used. Some calculations on this basis given

in previous editions showed that with a 20-part commutator the fluctuations were less than 1 per cent. of the whole, and with a 36-part commutator they were less than $\frac{1}{3}$ of 1 per cent. But as a matter of fact the distribution of the field in the part where coils are commuted does not obey any such law; and in the absence of information as to the exact way in which the induction of electromotive-force varies in the fringe of the field, such calculations may be very wide of the mark. It suffices to know that a 20-part commutator in a bipolar field gives fluctuations that are practically negligible, so that if it were not for other considerations—such as avoidance of sparking—it would be a useless refinement to employ commutators having more numerous segments.

Measurement of Fluctuation.—The relative amount of fluctuation in the current furnished by a dynamo may be observed by noticing the inductive effect on a neighbouring circuit into which is introduced a Bell telephone receiver. If the current is steady there will be no sound heard. If it fluctuate, each fluctuation will induce a corresponding secondary current in the telephone circuit, and the amount and frequency of the fluctuations may be estimated by the loudness and pitch of the sound in the telephone. The fluctuations in the current of a Brush arc-light dynamo are in this manner readily detected.

Effect of Non-simultaneous Commutation.—If the brushes are not so set that the sliding of contact under one brush is not accomplished at the same instant as that under the other brush, then it is clear that there will be slightly unequal electromotive-forces in the two halves of the armature circuit. This momentary inequality will die out, to be succeeded by another inequality (of opposite sign) when commutation occurs at the other brush. The effect will be the same as though a small alternating current having $2\,n\,c$ periods of alternation per second were made to act around the circuit of the armature. Such effects may be occasioned in armatures by various causes; if the number of sections in an armature be an odd number; if the number of conductors in all the sections are not alike or their connexions are unsymmetrical; or, lastly, if the contact-edges of the brushes do not lie exactly at opposite ends of a diameter.

Measurement of the Flux N.—An important problem is how to measure the actual number of magnetic lines that pass through the armature. This number is really best ascertained by calculation from the performance of the machine itself. The speed being observed by aid of a suitable speed-counter, the number of conductors round the armature being known, and the whole electro-

motive-force generated in the machine being measured by proper electrical methods, then it only remains to apply the fundamental formula, transformed so as to calculate back to N:—

$$N = 10^8 \times E \div n Z.$$

To measure E while the machine is running, it must either be run upon known resistances (so as to enable E to be calculated from Ohm's law); or E may be calculated by measuring (see p. 181) the difference of potentials at the brushes with a voltmeter, and then calculating from the resistance of and current in the armature the volts lost internally, which, added to the measured volts, make up the whole E.

THE MAGNETO-MACHINE AND THE SEPARATELY-EXCITED MACHINE.

In magneto dynamos, in which the field is due to permanent magnets of steel, N depends both on the magnetism of the steel and on the iron core of the armature. The number of lines that find their way through the armature is, however, lessened by the reaction of the armature when a large current is being drawn from the machine. If the magnetism of the field-magnets were so overpoweringly great, as compared with that due to the armature coils, that this reaction was insignificantly small, then, since our fundamental formula is:—

$$E = n Z N,$$

E would, for any given magneto machine, be directly proportional to n, the speed of rotation. But we know in practice that this is not the case. The number of turns by which the speed, at any output, exceeds the number that would be needed for strict proportion is called the *dead turns*. Suppose we turn a magneto machine at 600 revolutions per minute ($n = 10$, for then there will be 10 revolutions per second) and get, say, 17 volts of electromotive-force from it, then, if there were no reactions from the armature, turning it at 1200 revolutions per minute ought to give exactly 34 volts. This is never quite attained; though in many machines the

direct proportion very nearly holds good, so long as no current is drawn from the machine to give rise to demagnetizing effects. In that case the only reaction that would cause departure from proportionality is that possibly due to eddy-currents. If the speed and the total volts generated in the armature are observed, and plotted out against one another, the straightness of the "curve"—which ought to be a straight line sloping down to the origin—will show how nearly the theoretical condition is attained.

If the current in the armature is kept constant by increasing the resistances of the circuit in proportion to the speed, the demagnetizing action of the armature can be kept constant, even though the machine is giving out a current.

In some experiments[1] made by M. Joubert at different speeds, the electromotive-force was measured by an electrometer which allowed no current whatever to pass, and the theoretical law was almost exactly fulfilled. The observations are given below.

Speed	500	720	1070	revolutions per minute.
Electromotive-force ..	103	145	208	volts.

Potential at Terminals of a Dynamo. Lost Volts.—The potential at terminals of the magneto machine—and indeed of every dynamo—is, when the machine is doing any work, less than E, the total induced electromotive-force, because part of E is employed in driving the current through the resistance of the armature. The symbol e may be conveniently used for the difference of potential between terminals. Only when the external circuit is open, so that no current whatever is generated, $e = E$. It is convenient to have an expression for e in terms of the other quantities, seeing that when any current is being generated it is impossible to measure E directly by a voltmeter or by an electrometer, whereas e can always be so measured.

Let r_a be the internal resistance of the machine, that is to say the resistance of the armature coils, and of everything else in circuit between the terminals; and let R be the

[1] See also experiments by Mordey, *Journal I.E.E.*, xix. 233, 1890.

resistance of the external circuit. Then, by Ohm's law, if C be the current,

$$E = C\,(r_a + R).$$

But by Ohm's law also, if e be the difference of potential between the terminals of the part of the circuit whose resistance is R,

$$e = C\,R\,;$$

whence

$$\frac{e}{E} = \frac{R}{r_a + R}\,; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{III.}]$$

also

$$e = \frac{R}{r_a + R}\,E.$$

It is also convenient to note that

$$E = \frac{r_a + R}{R}\,e\,;$$

for this formula enables us to calculate the value of E from observations of e made with a voltmeter. But often the values of R are unknown: hence the following is more useful. By subtracting the second of the above equations from the first of them we get:—

$$E - e = C\,r_a,$$

or

$$e = E - C\,r_a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{IV.}]$$

This is equivalent to saying that the volts at the terminals are equal to the whole volts generated in the armature less the volts needed to drive the current C through the internal resistance r. The volts $C\,r_a$ which are thus not available in the external circuit, are called the *lost volts:* they will be less the smaller the internal resistance is. If e is observed by applying a voltmeter, then E can be found by adding to it the lost volts; and these can be calculated by measuring with an amperemeter the current flowing through the armature and multiplying this by the known internal resistance. In good modern dynamos the lost volts at full load do not amount to more than 2 or 3 per cent. of the whole voltage.

Relation between whole Electromotive-force and Difference of Potentials at the Terminals.—The essential distinction pointed out above between the whole electromotive-force E, and that part of it which is available as a difference of potentials at the terminals e, may be further illustrated by the following[1] geometrical demonstration.

In a machine (such as are chiefly dealt with later) in which e is constant, E will not be constant, except in the unattainable case of a machine which has no internal resistance. Let r represent the internal resistance of the machine, including that of the armature and of any magnet coils that are in the main circuit ($r = r_a + r_m$); then,

$$E = C R + C r = e + C r.$$

If E is constant, then e cannot be constant when C varies; and if e is constant, E cannot be. We have then two cases to consider:—

(1) E *constant.*—Take resistances as abscissæ and electromotive-forces as ordinates, and plot out (Fig. 122) O A = r, A N = R, O B = E. The line B N represents the fall of potential through the entire circuit. Of the whole electromotive-force O B, a part equal to C M is expended in

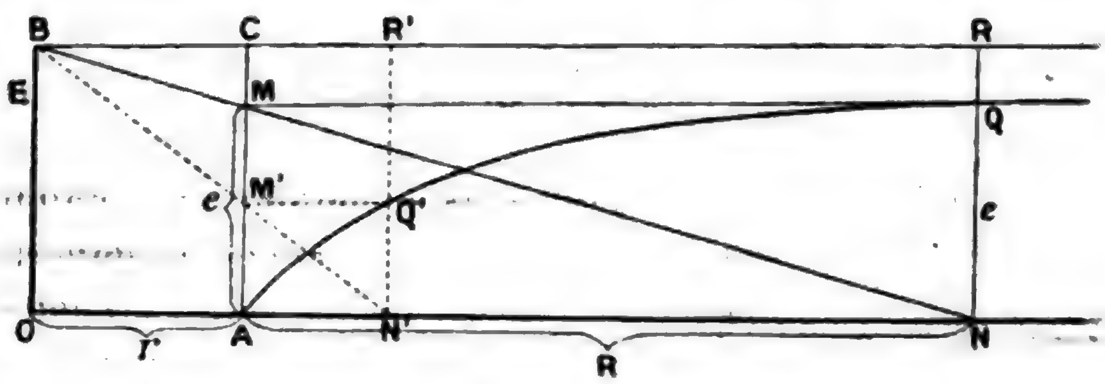


FIG. 122.

driving the current through the resistances r, leaving the part A M available as the difference of potential at the terminals, when the total resistance of the circuit is represented by the length from O to N. Accordingly, at N erect a vertical line N Q equal to A M. Take a less external resistance R' = A N' and by a similar process we find that the corresponding value

[1] *Elektrotechnische Zeitschrift*, iv. 161, April 1883.

of e is A M′ or N′ Q′. Similarly, any number of points may be determined; they will all lie on the curve A Q Q′, which therefore shows how, as the external resistance is increased the terminal potential rises, whilst the whole electromotive-force remains constant and is represented by the horizontal line B R. The equation of this curve is given by the condition

$$\frac{E - e}{E} = \frac{r}{R + r},$$

whence $(E - e)(R + r) = E\,r =$ constant; which equation is the equation of an equilateral hyperbola having O B and B R as asymptotes.

(2) *e constant.*—As in the preceding case, $O\,A = r$; $A\,N = R$; and $A\,M = e$. From N (Fig. 123) draw the line

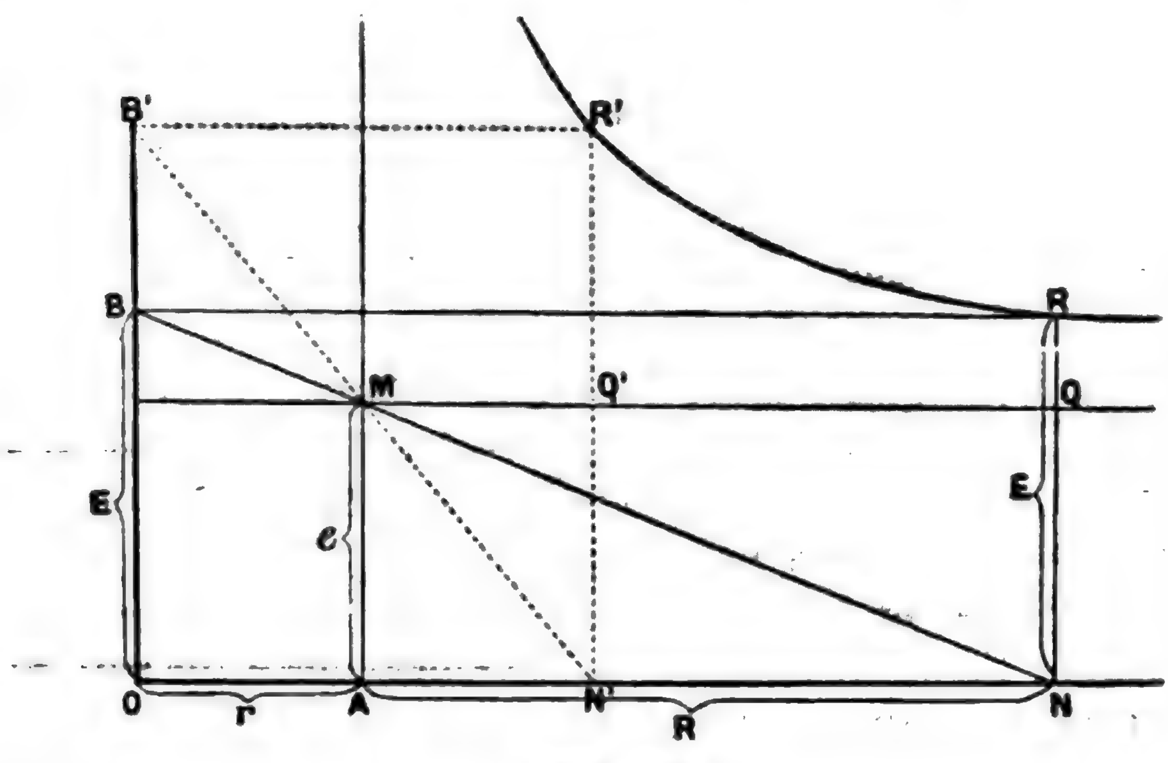


FIG. 123.

N M and produce it backwards to B. Then O B represents that value of E which will give e volts at terminals when $R = N\,M$. Accordingly set off at N the line $N\,R = O\,B$. In a precisely similar way draw N′ B′, to correspond with any other value of R, and make N′ R′ equal to O B′. N′ R′ represents the value of E when the value of the external resistance R is equal to A N′. By determining other values we obtain

the successive points of the curve R R', which shows how the whole electromotive-force must vary in order to maintain a constant difference of potentials at the terminals, as represented by the horizontal line M Q. The equation to this curve (also an equilateral hyperbola) is given by the condition

$$\frac{E - e}{r} = \frac{e}{R}$$

or

$$(E - e) R = e r = \text{constant}.$$

The Separately-excited Dynamo.—For separately-excited dynamos the same formulæ hold good as for magneto dynamos; but in this case N depends upon the strength of the independent exciting current.

In estimating the nett (or commercial) efficiency of a separately-excited dynamo, the energy spent per second in exciting the field-magnets ought to be taken into account.

Characteristic of Magneto Machine, and of Separately-excited Dynamo.—In the magneto dynamo the magnetism of the steel magnets is approximately constant. So is the magnetism in the iron of separately-excited machines if the exciting current is kept constant. This has given rise to a common idea that in such machines the electromotive-force depends on the speed alone. This is not true. For owing to the cross-magnetizing and demagnetizing tendency of the currents in the armature coils, the number of magnetic lines that actually traverses the armature core diminishes when the currents in the armature are strong. The stronger the current in the armature the stronger the reaction. And, as explained on p. 84, the demagnetizing tendency increases with the lead given to the brushes. As will be explained (p. 196), it is convenient to plot out certain curves, known as *characteristics,* to exhibit the relation that subsists between the electromotive-force and the current under different conditions of speed, resistance, &c. Usually one of the conditions assumed is that the speed is constant. Such curves are particularly useful for studying the various reactions that exist between the field-magnet and armature.

A careful study of the characteristics of separately-excited dynamos was made by Mr. W. B. Esson,[1] who gave the following curve for a separately-excited dynamo having a modified Pacinotti ring armature. The line E (Fig. 124) represents the total electromotive-force if there were no reactions. The line *e* represents the values of the potential between the brushes of the machine as it would be if there were no reaction.

The curved line B gives the actually-observed values of *e* when different currents were taken from the machine. The greater drop at the lower end of the curve is probably due to the greater demagnetizing effect when there is a considerable lead at the brushes. The characteristic always shows such downward curvature more when the field-magnets are weakly excited.

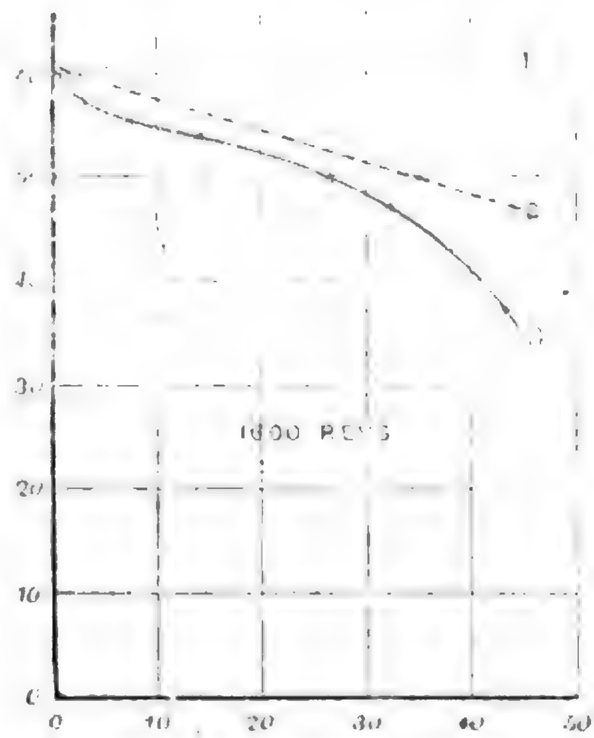


FIG. 124.—CHARACTERISTIC OF SEPARATELY-EXCITED DYNAMO.

Efficiency and Economic Coefficient of Dynamos.—Suppose that we know the actual mechanical horse-power applied in driving a dynamo. This can be measured directly either by using a transmission dynamometer, or by taking an indicator diagram from the steam engine that is driving it, or, in certain special cases where the field-magnets can be pivoted or counterpoised, by applying the method originally pursued by the Rev. F. J. Smith, and later described by M. Marcel Deprez and by Professor Brackett, in which the actual mechanical interaction between the armature and field-magnets is utilized to measure the horse-power used in driving the machine. If, then, we know the mechanical horse-power applied, and if

[1] *Electrical Review*, xiv. 393, April 1884. See also papers by M. Marcel Deprez, *Comptes Rendus*, xciv. pp. 15 and 86, 1882.

we measure the output of electric horse-power of the dynamo, we have by comparing the mechanical power absorbed with the electric power developed, a measure of the *efficiency* of the dynamo. It must, of course, be borne in mind that part of the electric energy developed is inevitably wasted in the machine itself, in consequence of the resistance in the wire of the armature, and, in the case of self-excited dynamos, in the wire of the field-magnet coils. There must, therefore, be drawn the distinction mentioned on p. 107 between the gross efficiency of the machine, or as it is sometimes called, its "efficiency of electric conversion," and its nett efficiency or commercial efficiency. We must, however, have the means of measuring the electric output of the dynamo.

As is well known, the energy per second of a current is expressed as the product of two factors, namely, the number of *amperes* of current, and the number of *volts* of potential between the two ends of that part of circuit in which the energy to be measured is being expended. The number of amperes of current is measured by a suitable amperemeter; the number of volts of potential by a suitable voltmeter. The product of the volts into the amperes expresses the electric energy expended per second, in terms of the unit of power denominated the *watt* (1000 watts = 1 *kilowatt*). As 1 horse-power is equal to 746 watts, the number of volt-amperes (*i.e.* of watts) must be divided by 746 to give the result in horse-power. If C represents the current in amperes, and e the difference of potential in volts, then the number of watts of power, for which we may use the symbol w, may be written

$$w = e\,\mathrm{C} \div 746. \quad \ldots\ldots \quad [\mathrm{V.}]$$

The ratio of the useful electrical power realized in the external circuit to the total electric power that is developed in the armature is called the "electrical efficiency" or "economic coefficient" of the machine. It may be expressed algebraically as follows:—If through an armature there is flowing a current of C_a amperes, and its total electro-

motive-force be E volts, then its total electric activity will be

$$= E\, C_a \text{ (watts)}.$$

If the volts of pressure between the terminals of the dynamo be e, then the useful activity is

$$= e\, C \text{ watts}.$$

Using the symbol η for the "economic coefficient," or so-called "electrical efficiency," we have

$$\eta = \frac{\text{useful activity}}{\text{total activity}} = \frac{e\, C}{E\, C_a},$$

or, if the machine has no shunt, so that C and C_a are the same thing,

$$\eta = \frac{e}{E}.$$

But we know that the ratio $\frac{e}{E}$ depends on the relation of the internal and external resistances, for

$$\frac{e}{E} = \frac{R}{r + R} \text{ (see equation [III.])},$$

where R is the resistance of the external circuit, and r the internal resistance (armature, magnets, &c.) of the machine. Hence, for a series dynamo or a magneto machine,

$$\eta = \frac{R}{r + R}. \quad . \quad . \quad . \quad . \quad . \quad [\text{VI.}]$$

Obviously, this coefficient will approach more and more nearly to *unity* the more that the value of r can be diminished. For if a machine could be constructed of *no* internal resistance there would be none of the energy of the current expended in driving the current through the armature and wasted in heating its coils.

We shall see later on how the expression for the economic

coefficient η must be modified in the case of shunt dynamos and compound dynamos.

Remembering that the gross electric power of the machine is $E\,C_a$ watts, or, in horse-power $E\,C_a \div 746$, we have for the *gross efficiency*, or efficiency of electric conversion,

$$\frac{E\,C_a}{\text{H.P.} \times 746},$$

and for the *nett efficiency*, or useful commercial efficiency,

$$\frac{e\,C}{\text{H.P.} \times 746}.$$

It will be seen that, as the first of these expressions contains E, and the second e, the nett efficiency can be obtained from the gross efficiency by multiplying by η, the economic coefficient.

Variation of Economic Coefficient with Current.—It must be noticed before passing from this topic that since C, the current, enters into each of the expressions for efficiency as a factor, and as C depends not only on the resistance of the machine itself, but on that of the lamps, or other parts of the system which it is used to feed, the efficiency of the dynamo will differ at different loads. As a rule the efficiency of a dynamo is greater at low loads than at full load, owing to the circumstance that the heat-waste increases as the square of the current. This should be contrasted with the case of steam engines in which the efficiency is highest at full load.

THE SERIES DYNAMO.

In the series dynamo (see Fig. 125, also Fig. 39), there is but one circuit, and therefore but one current, whose strength C depends on the electromotive-force E and on the sum of resistances in the circuit. These are:—

R = the external (variable) resistance.
r_a = the resistance of the armature.
r_m = the resistance of the field-magnet coils.

By Ohm's law—

$$E = (R + r_a + r_m)\,C.$$

Also e, the difference of potential between the terminals of the machine, is

$$e = C\,R.$$

It is also convenient to find an expression for the difference of potential between the brushes of the machine; the volts measured here being greater than e, because of the resistance of the field-magnets; and less than E, because of the resistance of the armature coils. For this difference of potential between brushes we will use the symbol ϵ. Then, by Ohm's law, remembering that the current running through r_m and R is of strength C, we have

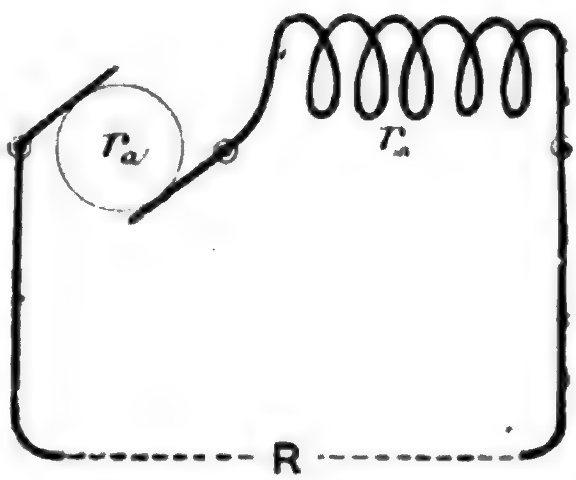


FIG. 125.

$$\epsilon = (R + r_m)\,C = E - r_a\,C;$$

whence, also,

$$e = E - (r_a + r_m)\,C.$$

Economic Coefficient of Series Dynamo.—From Joule's law of energy of current it follows that the economic coefficient η, which is the ratio of the useful electric energy available in the external circuit to the total electric energy developed, will be

$$\eta = \frac{\text{useful work}}{\text{total work}} = \frac{C^2\,R\,t}{C^2\,(R + r_a + r_m)\,t} = \frac{e}{E},$$

or

$$\eta = \frac{R}{R + r_a + r_m}. \qquad . \quad . \quad . \quad . \quad . \qquad \text{[VII.]}$$

This is obviously a maximum when r_a and r_m are *both* very small. They are usually about equal.

Example.—In a Phœnix arc-lighting dynamo, designed by Esson, $r_a = 3 \cdot 448$ ohms, and $r_m = 4 \cdot 541$ ohms. If C = 10 amperes, the lost volts will be 79·89.

Further than this we cannot go without introducing some kind of an expression to connect E with the number of ampere-turns in the exciting coils. If we introduce the convenient approximate formula of Frölich, as given on p. 143, we shall obtain some approximate dynamo formulæ. These were given in detail on pp. 401 to 410 of the third edition of this book; wherein also, at pp. 620, 627 and 632, were given the more elaborate developments by Frölich, by Clausius, and by Rücker.

THE SHUNT DYNAMO.

In the shunt dynamo, there are two circuits to be considered; the main circuit, and the shunt circuit. The symbols used have the following meanings.

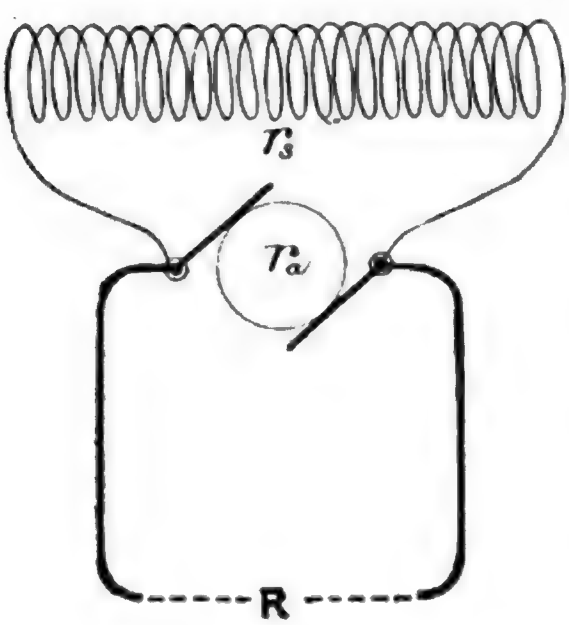


FIG. 126.

R = resistance of external main circuit (leads, lamps, &c.).

r_a = resistance of armature.

r_s = resistance of the shunt circuit (magnet coils).

C = the current in the external main circuit.

C_a = the current in the armature.

C_s = the current in the shunt circuit (the lost amperes).

Then, clearly,

$$C_a = C + C_s;$$

because the current generated in the armature splits into these two parts in the main and shunt circuits, and is equal to their sum.

We may call that part of the whole current which returns through the shunt, and is not available in the external circuit, the *lost amperes*: in a good modern machine they are at most

only 2 or 3 per cent. of the whole output of current. If e is the volts at the terminals, the lost amperes may be calculated as

$$C_{,} = e \div r_{,}.$$

For example, in the Kapp dynamo (Fig. 259), giving 200 *amperes* at a pressure of 105 *volts* at terminals, $r_{,}$ was 31 ohms, hence the *lost amperes* were 3·4, and total current in armature at full load 203·4 *amperes.*

Also, by Ohm's law, we have for e the electromotive-force between terminals,

$$e = C\,R,$$

and also

$$e = C_{,}\,r_{,}\,;$$

because the terminals for the main circuit are also the terminals for the shunt circuit.

Further, since the nett resistance of a branched circuit is the reciprocal of the sum of the reciprocals of the resistances of its parts, the nett external resistance from terminal to terminal is equal to $\frac{R\,r_{,}}{R + r_{,}}$; and hence it follows that

$$E = \left(r_{,,} + \frac{R\,r_{,}}{R + r_{,}}\right)C_{,,}.$$

We may at the same time find an expression for that part of the whole electromotive-force which is being employed solely to overcome the resistance of the armature, and which is, of course, the difference between E the total electromotive-force, and e the effective electromotive-force between terminals.

Ohm's law at once gives us

$$E - e = r_{,,}\,C_{,,}\,,$$

or

$$E - e = r_{,,}\,(C + C_{,}).$$

From this we also get

$$e = E - r_{,,}\,(C + C_{,}). \quad . \quad . \quad . \quad . \quad [\text{VIII.}]$$

We will also find an expression for E in terms of e, and the various resistances. Taking as above

$$E = \left(\frac{R\,r_s}{R + r_s} + r_a\right) C_a,$$

and writing for C_a its value as $C + C_s$, and for these e/R and e/r_s respectively, we get

$$E = e\left\{\frac{R\,r_s + R\,r_a + r_a r_s}{R + r_s} \times \frac{R + r_s}{R\,r_s}\right\},$$

or

$$E = e \times r_a\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right). \quad . \quad . \quad [\text{VIII. } \textit{bis.}]$$

It may be noted that the expression $\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right)$ is the sum of three conductances of three paths, and is therefore equal to the conductance of these three paths united in parallel with one another; that is to say, the conductance as measured from brush to brush with the external circuit and shunt circuit joined up. Or, if we write $\mathbb{R}$ for the resistance of the whole system of machine and circuit, as thus measured from brush to brush, then the equation may be written

$$E = e \times r_a / \mathbb{R}.$$

The economic coefficient η, is the ratio of the useful electric energy available in the external circuit to the total electric energy developed.

By Joule's law there is developed in t seconds in the external circuit

$$\text{useful work} = C^2 R\,t,$$

and in the same time there is wasted on heating,

$$\text{energy spent in shunt} = C_s^2\,r_s\,t,$$

and

$$\text{energy wasted in armature} = C_a^2\,r_a\,t;$$

whence

$$\frac{\text{useful work}}{\text{total work}} = \frac{C^2 R}{C^2 R + C_s^2 r_s + C_a^2 r_a}$$

$$= \frac{1}{1 + \dfrac{R}{r_s} + \dfrac{C^2 r_a + 2\,C\,C_s\,r_a + C_s^2\,r_a}{C^2 R}}.$$

Eliminating the values of currents this reduces to the form,

$$= \frac{1}{1 + \frac{R}{r_s}\left(1 + \frac{r_a}{r_s}\right) + \frac{r_a}{R} + 2\frac{r_a}{r_s}}.$$

Now, for brevity, write for the total internal resistance, $r_a + r_s$, the single symbol r—

$$\eta = \frac{1}{1 + \frac{R\,r}{r_s\,r_s} + \frac{r_a}{R} + 2\frac{r_a}{r_s}}.$$

For this ratio to be a maximum it is clear that,

$$\frac{d\left(1 + \frac{R}{r_s}\cdot\frac{r}{r_s} + \frac{r_a}{R} + 2\frac{r_a}{r_s}\right)}{d\,R} \text{ must } = 0,$$

or

$$\frac{r}{r_s^2} - \frac{r_a}{R^2} = 0;$$

whence

$$R^2 = \frac{r_a\,r_s^2}{r} = r_a\,r_s\,\frac{r_s}{r},$$

$$R = \sqrt{r_a r_s}\sqrt{\frac{r_s}{r}}, \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{IX.}]$$

or

$$R = r_s\sqrt{\frac{r_a}{r}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{IX}a.]$$

This equation determines what particular resistance of the external main circuit will give the best economy with given internal resistances. Now substitute this value in those terms of the equation for η which contain R, and we get as their values :—

$$\frac{R\,r}{r_s^2} = \frac{r}{r_s}\sqrt{\frac{r_a}{r}} = \frac{\sqrt{r_a\,r}}{r_s},$$

$$\frac{r_a}{R} = \frac{r_a}{r_s}\sqrt{\frac{r}{r_a}} = \frac{\sqrt{r_a\,r}}{r_s};$$

whence

$$\eta = \frac{\text{useful work}}{\text{total work}} = \frac{1}{1 + 2\frac{\sqrt{r_a\,r}}{r_s} + 2\frac{r_a}{r_s}}.$$

This may be still further simplified, for we know that the resistance of the shunt is very high compared with that of the armature, possibly from 300 to 3000 times as great. If, then, $\frac{r_a}{r_s}$ is so small a term in comparison with the other term as to be negligible, we get

$$\eta = \frac{1}{1 + 2\frac{\sqrt{r_a r}}{r_s}}; \quad . \quad . \quad . \quad . \quad . \quad . \qquad [X.]$$

and since r_a is small compared with r_s, r is very nearly equal to r_s, so that we may write, as an approximate equality,

$$\eta \doteqdot \frac{1}{1 + 2\frac{\sqrt{r_a r_s}}{r_s}};$$

or

$$\eta \doteqdot \frac{1}{1 + 2\sqrt{\frac{r_a}{r_s}}} \quad . \quad . \quad . \quad . \quad . \quad . \qquad [XI.]$$

This latter approximate value is identical with that given by Lord Kelvin in the Report of the British Association for 1881 : the equation No. [X]. is, however, more correct. It follows from equation [XI.] that the resistance of the shunt coil should be at least 324 times as great as the internal resistance of the armature, otherwise the efficiency will be lower than 90 per cent.

It may be pointed out that it follows from equation No. [IX.] above, that when the resistance of the armature is small compared with that of the shunt, so that r_s may be taken as equal to the value of r (which would be highly desirable if it could be attained in practice), then we should have

$$R = \sqrt{r_a r_s}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad [XII.]$$

that is to say, when the proportion between r_a and r_s is made as favourable as possible, then the best external resistance to work with from the economic point of view is that resistance which is a geometric mean between the resistances of the armature and of the shunt coils, and any departure from this will diminish the value of the economic coefficient.

In the case of machines for which an electrical efficiency not exceeding 90 per cent. is sufficient, the rule works out as follows:—Ascertain what number of lamps will be the usual full load: reckon the resistance of them when connected to the mains. Let the armature resistance be only one-twentieth of this; and let the shunt resistance be twenty times as great as this. In this case about 4 per cent. will be wasted in the armature, and about 4 per cent. in the shunt, leaving a margin of a little over 90 per cent. for the economic coefficient.

In a shunt machine described by Sir C. W. Siemens in the *Philosophical Transactions*, 1880, the results were:—

—	Armature.	Shunt Magnet	r_s / r_a.	η observed per cent.
Siemens	0·204	11·26	48·4	69·0

The Edison-Hopkinson machine, described on p. 353, gave:—

Resistance when cold	0·009947	16·93	1702	93·66

The Kapp dynamo alluded to above, p. 191, and described on p. 357, gave, including the series coil with the armature:—

(Cold)	0·0306	29·133	952	
				92
(Warm)	0·0329	31·08	945	

CHAPTER X.

CHARACTERISTIC CURVES.

So many practical problems in the construction of dynamo-electric machines are in the present state of science solved by the use of graphic diagrams, and particularly by the use of certain curves technically called *characteristics*, that the method of constructing and using them forms an important part of the theory of the dynamo. For many practical purposes no other method is half so useful.

The characteristic curve stands indeed to the dynamo in a relation very similar to that in which the indicator diagram stands to the steam engine. As the mechanical engineer, by looking at the indicator diagram of a steam engine, can at once form an idea of the qualities of the engine, so the electrical engineer, by looking at the characteristic of the dynamo can judge of the qualities and performance of the dynamo. The comparison may even be said to reach farther than this.

The steam-engine indicator diagram serves two purposes which, though not unconnected with one another, are yet distinct. When the scale on which the diagram is drawn is known, it gives direct information as to the horse-power at which the engine is working, depending on the total area enclosed by the curve, and quite irrespective of its form. But even though the actual scale be not known, the details of the form of the curve at its various points give very definite information to the engineer as to the working of the engine, the perfection of the exhaust, the setting of the valves, the efficiency of the cut-off, and the adequacy of the supply pipes and port-holes of the valves.

So also the characteristic curve of the dynamo may serve two functions. When the scale on which it is drawn is known

it tells the horse-power at which the dynamo works ; nay, can indicate at what horse-power the dynamo may be worked to the greatest profit. But even though the actual scale be not known, the details of the form of the curve afford definite information as to the conditions of the working of the machine ; the degree of saturation of its magnets, the sufficiency of the field-magnets in proportion to the armature, and the goodness of the design in several respects.

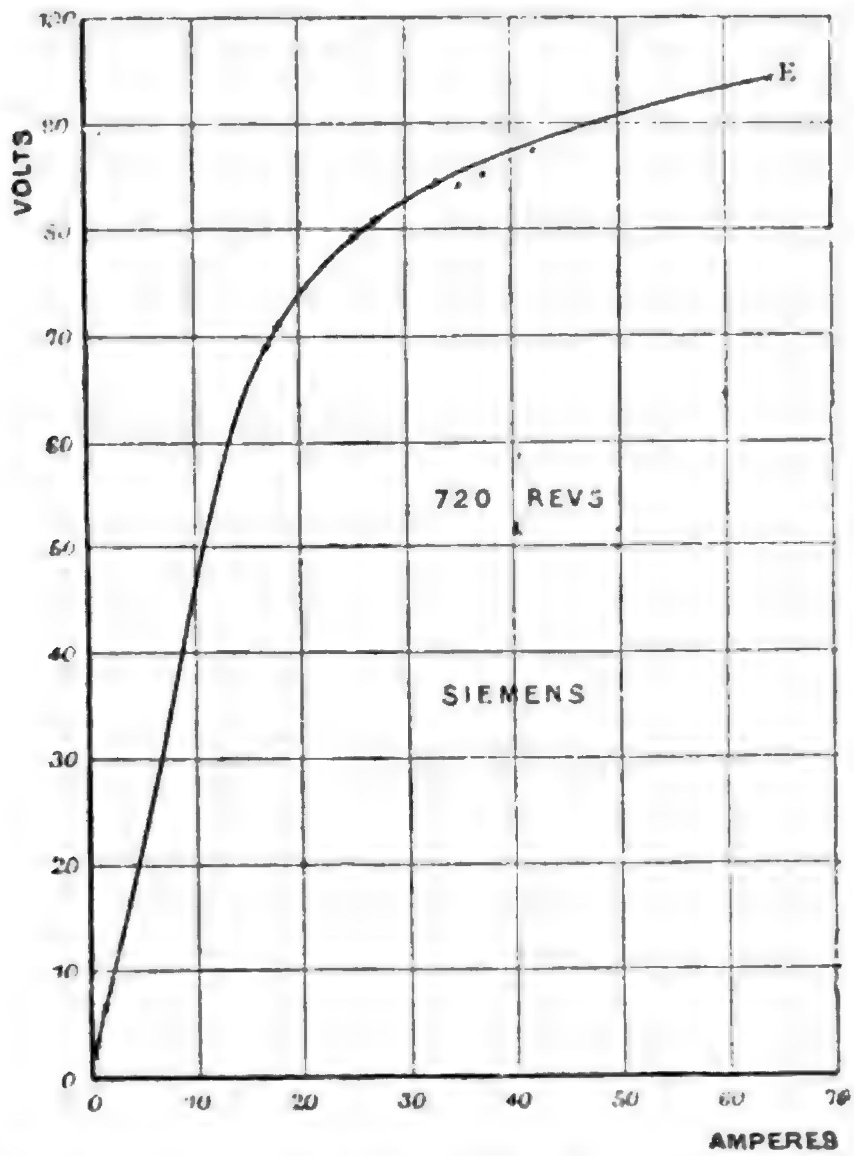


FIG. 127.—CHARACTERISTIC CURVE OF A SERIES DYNAMO.

The first self-exciting dynamos put into commerce were series wound ; they were found to possess a most puzzling instability of behaviour, sometimes losing their current altogether, and refusing to excite themselves. This and other peculiarities were not understood until the curves of their performance were studied.

The suggestion to represent the properties of a dynamo machine by means of the characteristic curve is due to Dr. Hopkinson, who in 1879 described such curves to the Institution of Mechanical Engineers, and gave the curve of the Siemens dynamo reproduced in Fig. 127. The name of "characteristic" was assigned in 1881 by M. Marcel Deprez[1] to Hopkinson's curves; and the excellence of the name has been attested by its general adoption.

Dr. Hopkinson's object was to represent the relation subsisting between the electromotive-force and the current; he therefore constructed from observations a curve in which the abscissæ measured horizontally represent the number of amperes of current flowing, and the vertical ordinates the corresponding values of the electromotive-force. The following table gives the observed values C of the current, and E the electromotive-force, of a certain series-wound dynamo.

EXPERIMENTS ON SIEMENS DYNAMO AT SPEED OF 720 REVOLUTIONS PER MINUTE.

Current (in amperes). C	Resistance (in ohms). R	Electromotive-Force (in volts). E
0·0027	1025	2·72
0·48	8·3	3·95
1·45	5·33	7·73
16·8	4·07	68·4
18·2	3·88	70·6
24·8	3·205	79·5
26·8	3·025	81·1
32·2	2·62	84·4
34·5	2·43	83·8
37·1	2·28	84·6
42·0	2·08	87·4

[1] Vide *La Lumière Électrique*, Dec. 3, 1881; where, however, Deprez gives a method of observation that is open to the objection that it neglects the armature reactions.

It may be remarked that the electromotive-force E is the total electromotive-force generated in the machine, and must not be confounded with e the difference of potential between the terminals as measured by a voltmeter, or other similar instrument. In many cases we now prefer to plot e instead of E; but that was not Hopkinson's original method. He determined E by measuring C and multiplying it by the total resistance of the circuit; for by Ohm's law $C R = E$. It should also be remarked that the dynamo was a "series dynamo," shunt-wound machines not having at that date come into vogue.

Before entering into other points, it may be worth while to consider the meaning of the curve. It begins at a point a little above the origin. This shows that there was a small amount of residual magnetism remaining permanently in the field-magnets. The curve ascends at first at a steep angle, then curves round and eventually assumes a nearly straight course, but at a gentler slope than before. As the speed is constant —it was maintained at 720 revolutions per minute in Hopkinson's experiments—the only variable of importance is the magnetism. As this rises and grows toward a maximum, so does the induced electromotive-force. We might therefore expect, as Hopkinson points out, that this curve should exhibit peculiarities of form similar to those of the curve which represents the relation between the magnetizing current and the magnetization of an electromagnet; and a comparison of Fig. 127, the "characteristic" of the series dynamo, with Fig. 86, the "magnetization curve" of an electromagnet, will suffice to reveal the analogy. It must, however, be pointed out that the magnetism is affected by the reaction of the armature.

It is possible for a dynamo to be made to draw its own characteristic by mechanically moving the pencil relatively to the paper (as in steam indicators) by means of two electromagnets, one of them being excited by the main current, the other being connected as a shunt to the terminals of the machine.

Dr. Hopkinson, in the paper alluded to, and in a second one published in the *Proc. Inst. Mech. Engin.*, in April 1880, p. 206, pointed out a great many of the useful deductions to be drawn from a consideration of these curves. Some other deductions have been made by M. Marcel Deprez, for which the reader is referred to *La Lumière Électrique*, of Jan. 5th, 1884. Dr. Frölich has also published several important papers on the subject in the *Elektrotechnische Zeitschrift* for 1881 and 1885. Dr. Hopkinson returned to the subject in a lecture before the Institution of Civil Engineers, "On Some Points in Electric Lighting," April 1882. See also his book on *Dynamo-Electric Machines* (London 1893).

As mentioned at the beginning of this chapter, if the characteristic curves are drawn to scale the output of the dynamo may be read off from them in horse-power. The unit of electric power, the product of one volt into one ampere, has been called by the special name of one *watt*. One watt (or volt-ampere) is equal to $\frac{1}{746}$ of a horse-power. To calculate the horse-power (electrical) evolved in the circuit when the dynamo is running with any number of lamps in circuit, two measurements have ordinarily to be made—the volts of electromotive-force and the amperes of current. These must then be multiplied together and divided by 746 to obtain the horse-power. But if the characteristic of the dynamo at the particular speed be known, a reference to the curve will show at once what the electromotive-force is that corresponds to any particular current. For example, in the Siemens dynamo examined by Hopkinson, the characteristic of which is given in Fig. 127, p. 197, suppose the dynamo was working through such a resistance as to give 30 amperes when running at 720 revolutions, we see at once that the corresponding electromotive-force is 83. Hence

$$\frac{83 \times 30}{746} = 3{\cdot}3 \text{ horse-power.}$$

Now to obviate such calculations we may plot out on the diagram some additional curves crossing the characteristics and mapping them out into equal values of horse-power. These "horse-power lines" are nothing else than a set of rect-

angular hyperbolas. For example, the 1-horse-power line will pass through all the points for which the product of volts and amperes is equal to 746. It will therefore pass through the point corresponding to 74·6 volts and 10 amperes; through 37·3 volts and 20 amperes; through 14·92 volts and 50 amperes, &c., because the product in each of those cases is equal to 746 watts or 1 horse-power. The 2-horse-power line

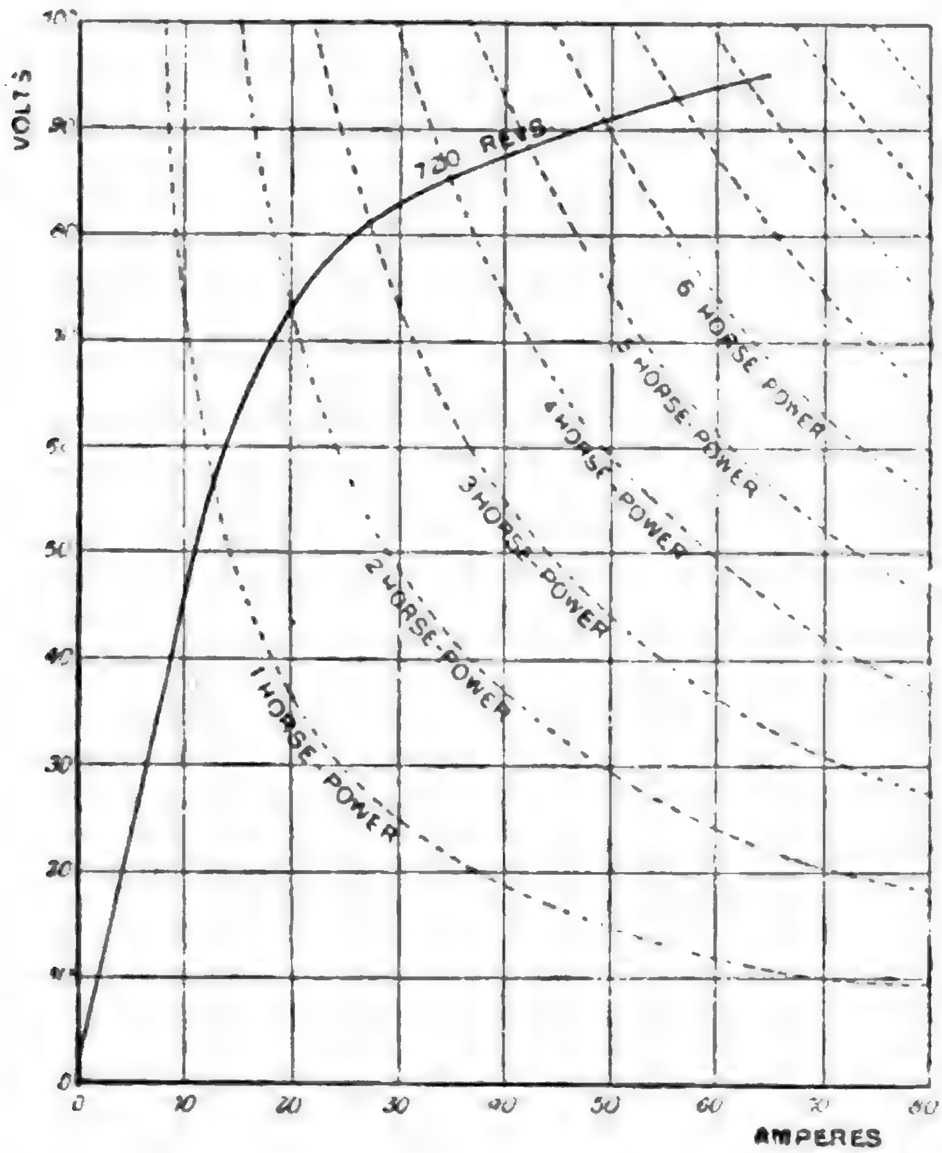


FIG. 128.—CHARACTERISTIC WITH HORSE-POWER LINES.

will pass through points whose product values are equal to 746 × 2, and the other lines in the same way. Fig. 128 shows the characteristic of the Siemens machine, reproduced from Fig. 127 above, but with the horse-power lines added.

In this case the volts plotted are the total electromotive-force E, of the dynamo, and therefore the horse-power represents the gross electric output. If instead of E we had

plotted the values of e, the volts at the terminals, we should have had a slightly different curve, representing the nett output in the external circuit available for useful purposes.

If the vertical and horizontal scales are not chosen equal, the horse-power lines, though hyperbolæ, are of course distorted.

"External" Characteristics or Terminal Potential Curves.—The name *external characteristic* may be given for the sake of distinction to those curves which exhibit the relation between the potentials and the currents of the external circuit. In the series dynamo it is a simple matter to derive one of these curves from the other, provided the internal resistance of the machine (armature and field magnets) is known. In the Siemens dynamo examined by Hopkinson in 1879, and of which Figs. 127 and 128 give the total characteristic, the total internal resistance was 0·6 ohm. The curve is reproduced for a third time in Fig. 129, where it is marked "E." Now to force a current of 10 amperes through a resistance of 0·6 of an ohm would require a difference of potential of 6 volts between its terminals. Looking at the curve, we see that the whole electromotive-force, corresponding to 10 amperes, was about 46·5 volts. Of this number, 6 were employed as mentioned, in overcoming the internal resistance, leaving 40·5 volts as the available potential between terminals. Further, when the current was running at 50 amperes, there must have been no less than 30 volts *lost* in overcoming the internal resistance of 0·6 ohm: and as the value of E for this current is 90·5 volts, there remain 60·5 volts for e. There are now two ways open to us of representing these matters on our diagram. They are both shown in Fig. 129. The line J is drawn through the origin, and through the values of 6 volts for 10 amperes and 30 volts for 50 amperes. (The tangent of the slope of the line J is equal to $6 \div 10 = 0·6$. We shall see later that this slope represents the internal resistance.) Then if the heights of the ordinates from the base line up to the line E represent total volts induced, and if the heights of the ordinates from the base line up to the line J represent the corresponding volts lost in overcoming internal resistance it

follows that *the difference of potentials at the terminals will be represented by the differences of the ordinates between the lines* J *and* E. This is the first way of representing those differences of potentials. The second way is to cut off from the tops of the ordinates portions equal to those of the line J. This amounts to subtracting the internal volts, which as shown in the algebraic theory are equal to C ($r_a + r_m$), from E, and so obtaining the values of e. These are plotted out in the curve

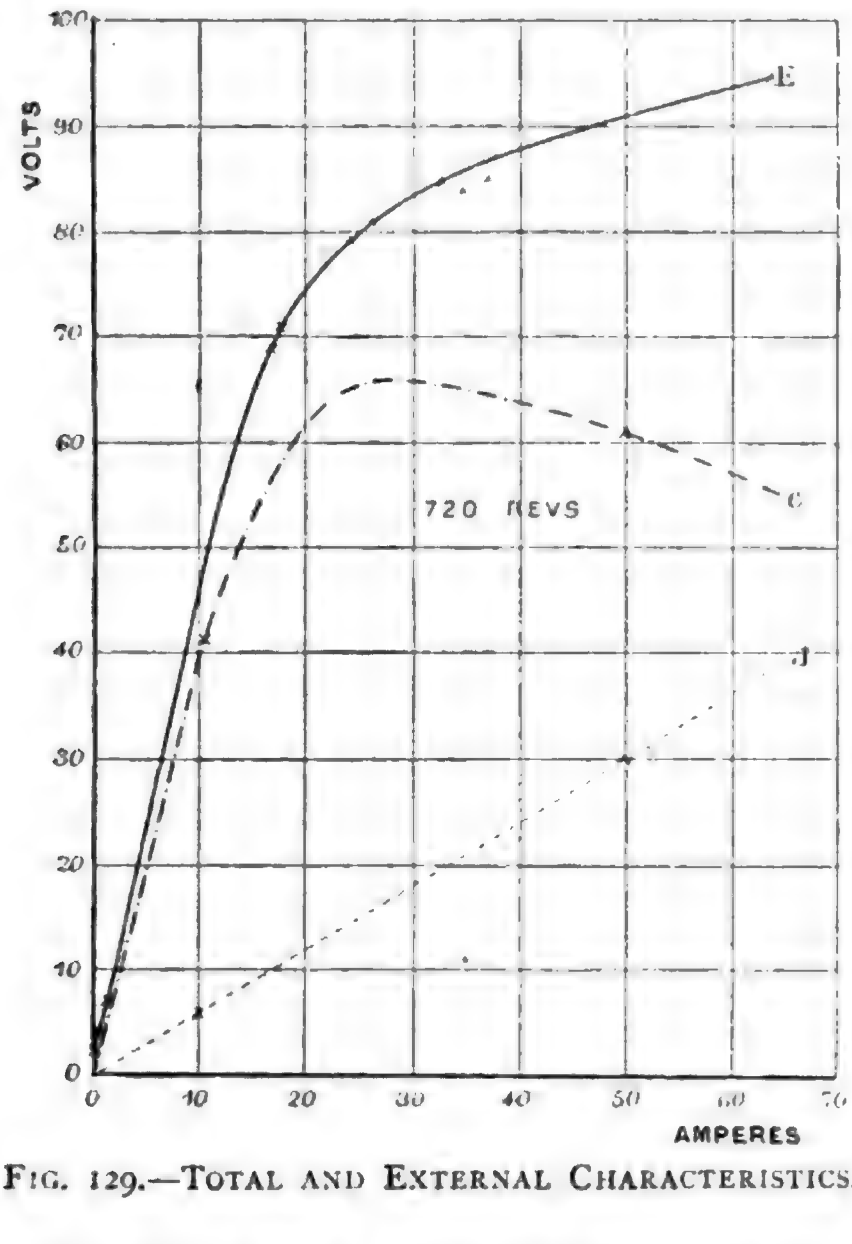


FIG. 129.—TOTAL AND EXTERNAL CHARACTERISTICS.

marked "e" in the figure; and as this curve represents the available electromotive-force in the external circuit, it obtains the name of *external characteristic* or terminal potential curve. As a matter of fact it is more usual to reverse the operation. The terminal potential values are easily observed with a voltmeter and the current with an ampere-meter. Then the external curve for e and C is plotted; and by *adding* to the

ordinates the corresponding values of the lost volts, we so obtain the curve for E and C. If there is permanent magnetism in the magnets, the characteristics will not start from the origin, but from a point a little above it.

Characteristics of Series Dynamo.—The Siemens dynamo of which the characteristic is given in Fig. 127 was a series dynamo. For the sake of comparison the characteristic is given in Fig. 130 of an "A" Gramme machine also series-wound. This machine had, when it was measured by M. Marcel Deprez, 0·41 ohm resistance in the armature coils and 0·61 ohm in the coils of the field-magnets. Two characteristics are given; one corresponding to a speed of 1440, the other to a speed of 950 revolutions per minute. The horse-power lines are shown in dot also.

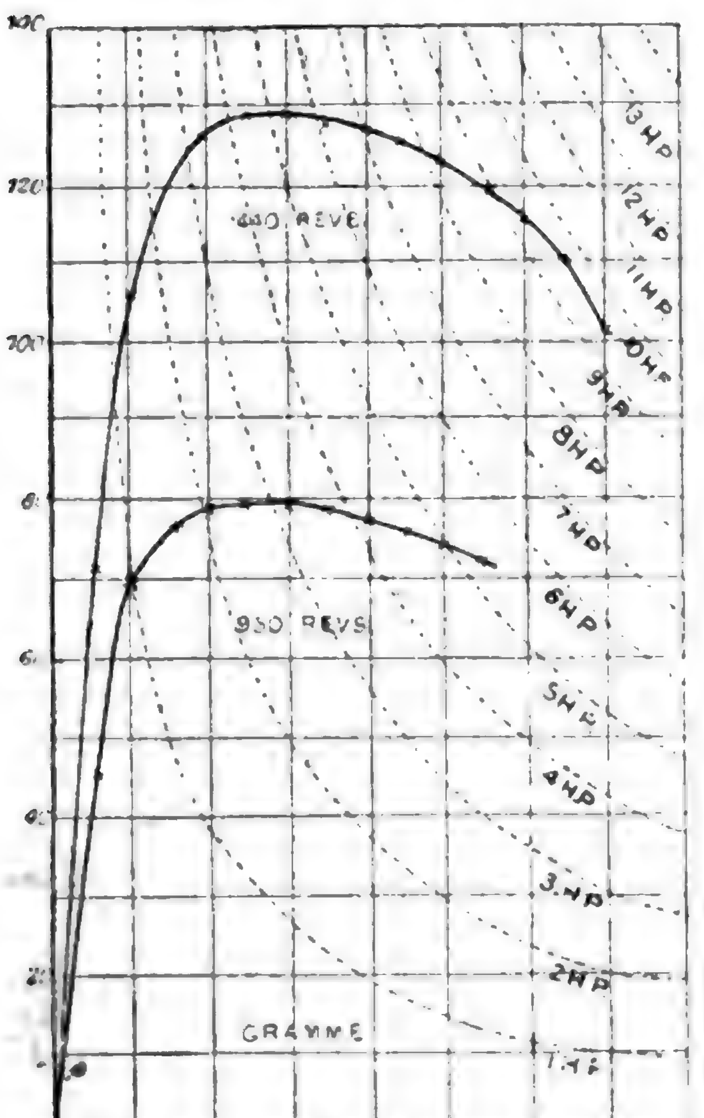


Fig. 130.—Characteristic at Different Speeds.

In the series dynamo the magnetization of the magnets increases with the current, and therefore, at first, the electromotive-force increases also, giving the first straight portion of the curve. As the magnets approach saturation the curve turns, and, as the reactions due to the current in the armature now become of relatively great importance, flattens itself and ultimately turns down again; the increased lead of the brushes greatly adding to the effect. The fall in the characteristic is always greater in the case of weak field-magnets. It also

occurs most in those machines in which the core of the armature is more nearly saturated than are the cores of the field-magnets; for as with large currents the armature cores get saturated, the magnetic leakage becomes relatively greater.

One more curve of a series-wound dynamo is given in Fig. 131. This is a small Brush machine (intended to supply a single arc light) of the early pattern, with solid iron ring, in which, owing to the peculiar arrangement of the coils (see p. 454), the reactions of the armature make themselves known by a very extraordinary down-bending of the characteristic. This is partly due to the arrangements for cutting out a pair of coils as they approach the neutral point. It will be noticed that the maximum horse-power of this small machine is $1\frac{3}{4}$ horse; and that this value is only obtained when the reactions have already set in. This diminution in the electromotive-force is in practice a real advantage. Should the machine be accidentally short-circuited while running, the reactions of the armature prevent the production of an injuriously large current, which might overheat the coils. It is an advantage in machines for arc-lighting, where a nearly constant current is required, to employ machines with drooping characteristics, and to work them at this part of the curve (see p. 466).

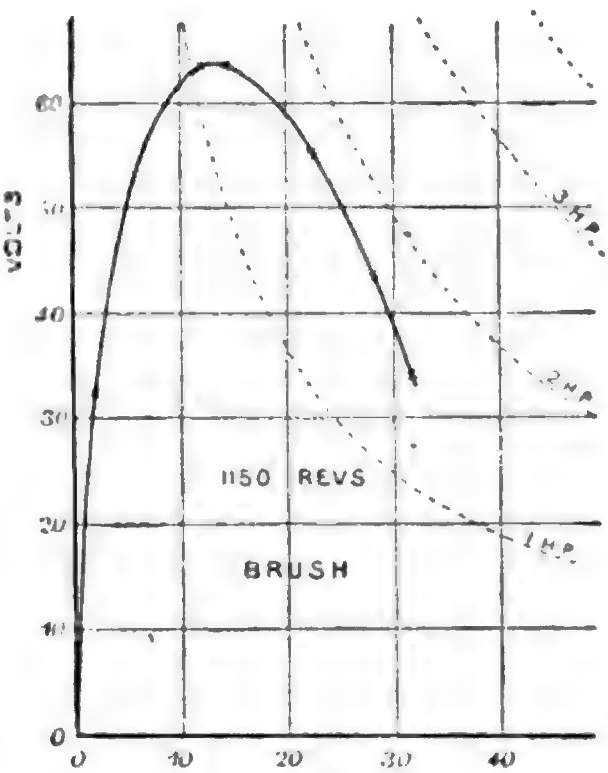


FIG. 131.—DROOPING CHARACTERISTIC.

Relation of Characteristic to Speed.—The electromotive-force generated in a rotating coil or armature would be strictly proportional to the field, were it not for the reactions of the armature. Now in a series dynamo, the field depends on the current; and, if the current is kept constant (by adjusting the resistances), the field will also be constant

even though the speed be varied. If therefore the characteristic of a machine be known at any speed, its characteristic for any other speed can be found by the very simple process of increasing the ordinates of the curve in a similar proportion. Take, for example, the case of the Gramme dynamo, of which a characteristic at the speed of 250 revolutions is given in Fig. 130. The characteristic at 1440 could be calculated from it by increasing the ordinates in the proportion of $\frac{1440}{950}$. Thus we see from the lower curve that when the current was 20 amperes the electromotive-force was 79 volts. Then $79 \times 1440 \div 950 = 119{\cdot}7$ volts. The actual electromotive-force observed at the speed 1440 and with current at 20 amperes was 127 volts. There is a slight discrepancy here, and indeed always; for dynamo machines behave invariably as if a certain number of the revolutions did not count electrically. If the number of "dead turns" (see p. 88) were here reckoned as 140, the number of volts calculated by theory would agree very exactly with that observed.

Resistance in the Characteristic.—In the characteristic we have volts plotted vertically and amperes horizontally. Now by Ohm's law, volts divided by amperes give ohms. How can this be represented in the characteristic? Suppose, for example, it is required to represent the resistance of the circuit corresponding to some particular current. Let Fig. 132 be the characteristic of the dynamo in question, and it is desired to know what is the resistance corresponding to the state of things at the point marked P. Draw the vertical ordinate P M, and join P to the origin O. The line P O has a certain slope, and the angle of its slope is P O M. Now P M is equal to the electromotive-force under consideration, and O M is the current. Therefore, by Ohm's law,

$$\text{Resistance} = \frac{\text{electromotive-force}}{\text{current}} = \frac{\text{P M}}{\text{O M}};$$

but

$$\frac{\text{P M}}{\text{O M}} = \tan \text{P O M};$$

therefore the resistance = tan P O M. Put into words, this is :—*The resistance corresponding to any point on the characteristic is represented by the tangent of the angle made by joining the point to the origin.* An easy way of reckoning these tangents is shown in Fig. 132. At the point on the horizontal line corresponding to 10 amperes erect a vertical line. A line drawn from the origin at an angle whose tangent is = 1 (namely 45°) would cross this vertical line at a point opposite the 10-volt mark. This point may then be called 1 ohm, and equal distances measured off on this line will constitute it a scale of resistances. In Fig. 132 the resistance corresponding to point P of the characteristic is seen to be about 1·2 ohm on the scale of resistances. Now P is placed at 51·3 volts, and the current is 43·2 amperes. Dividing one by the other, we get 1·18 ohm. Calculations are sometimes more conveniently made by graphic construction.

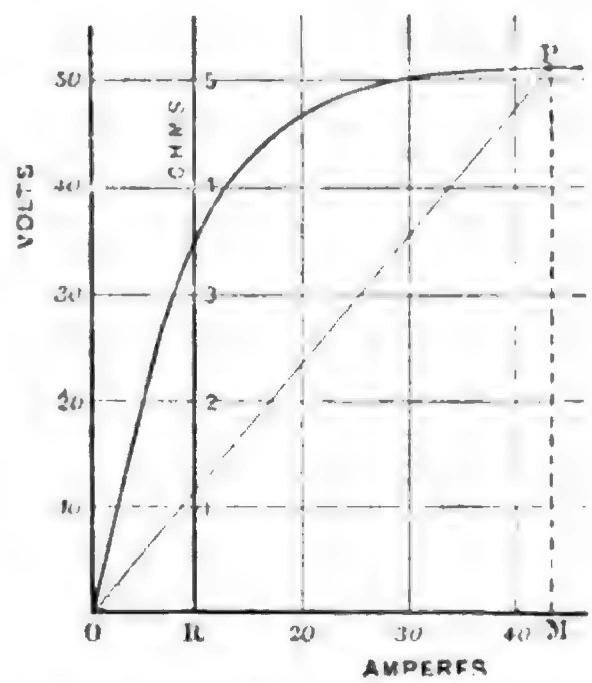


FIG. 132.—METHOD OF REPRESENTING RESISTANCE GRAPHICALLY.

If in the actual dynamo the resistance of the circuit were gradually increased, we should have the point P displaced along the curve backwards towards the origin, the volts and amperes both falling off, and the steepness of the line O P increasing. When O P arrived at a certain steepness it would practically form a tangent to that part of the characteristic which is nearly straight, and then any very small increase in the resistance would cause the dynamo to lose its magnetism, from lack of current to magnetize the magnets.

Resistance may be similarly represented on the characteristics of any dynamos ; but if the characteristic is drawn for the *external* current and the *external* difference of potential, then the resistance so represented will be the *external* resistance.

Relation of Characteristic to Winding of Armature and

Field-magnets.—Suppose the armature of a machine to be re-wound with a larger number of turns of proportionally thinner wire. What will be the result at the same speed as before? The resistance will be increased somewhat, and the electromotive-force also will be higher. Let Fig. 133 represent the characteristic of the machine as it was when there were X turns of wire on the armature. How must it be drawn when the number is increased to X′? Let P represent a point corresponding to a certain strength of current. Taking the new armature, let the external resistance be varied until the current once more comes to the same value. The magnets are now magnetized exactly as strongly as before; but there are X′ turns of wire cutting the magnetic flux, instead of X. The electromotive-force will therefore also be greater in the like proportion. Draw therefore P′ C so as to have the proportion P′ C : P C : : X′ : X. All other points on the new characteristic can be obtained by similarly enlarging the ordinates in the same ratio.

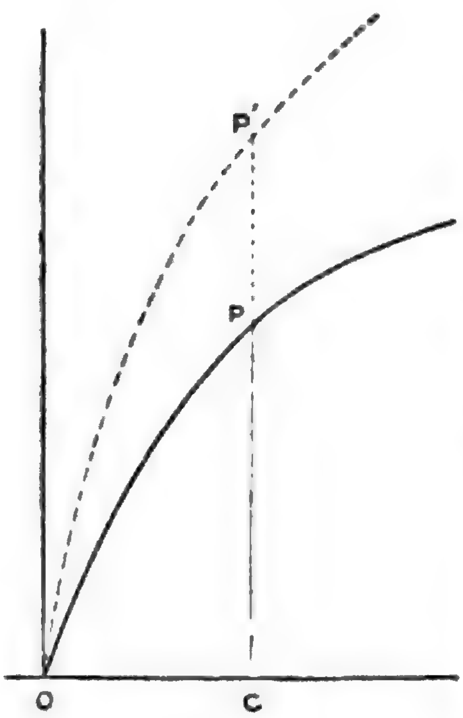


FIG. 133.

It will be evident from this that increasing the number of turns of wire in the armature has the same effect as increasing the speed of driving This shows that *slow speed* dynamos (for use on ships, &c.) may be made to give the requisite electromotive-force provided the number of turns of wire be relatively increased. This involves, however, a sacrifice of economy, because of the increase of resistance in the armature, or of prime cost if thicker wire is used.

The effect of altering the number of turns of wire on the field-magnets can also be traced out on the characteristic diagram. Suppose the number of turns in the magnetizing coil be S, and that we re-design the machine, increasing the number to S′ turns. What will the result be? In this case we shall get the same electromotive-force when driving at the same speed as before, provided the magnets be equally

magnetized. But if the current goes S′ times round instead of S we shall want a current only $\frac{S}{S'}$ as strong as before, to produce the same magnetization. To get the new characteristic then (see Fig. 134), draw P E horizontally. P E = C O = the current corresponding to electromotive-force E. Find P′ such that P′ E : P E :: S : S′; then the new characteristic will pass through P′. Similarly, all other points of

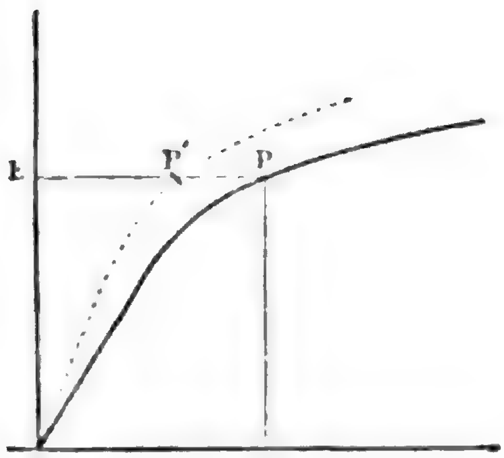


FIG. 134.

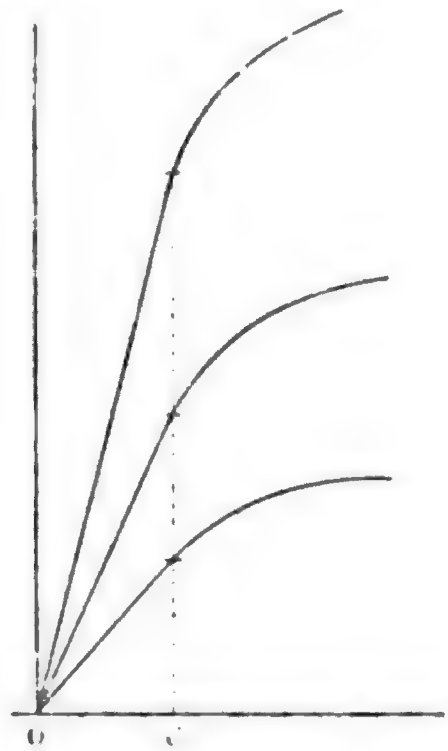


FIG. 135.

the new characteristic may be determined by reducing their abscissæ in a similar proportion.

It must be noted that these two processes are not admissible for the characteristics of shunt-wound machines.

Critical Current of Series Dynamo.—From the fact that the characteristics for different speeds differ only in the relative scale of the ordinates, an important consequence may be deduced. The first part of every characteristic for any speed is nearly straight up to a point where for that speed the electromotive-force is nearly two-thirds of its maximum value. When the current is such that the electromotive-force has attained to this value, any very small change either in the speed of the engine or in the resistance of the circuit produces a

great change in the electromotive-force, and therefore in the current; therefore since this critical case occurs always with the same current (see Fig. 135), this current—corresponding to the point on all the curves where the straight line begins to turn—may be called the "critical current" of the dynamo. This is the explanation of the puzzling instability remarked on p. 197. The series dynamo only "builds" its magnetism when the resistance is low enough, and when excited and running will "unbuild," or lose its magnetism, if the resistance of the circuit is increased too much. Each series dynamo has its own critical current, and it will not work with a less one; for a less one will not adequately excite the field-magnets. Since with each speed the characteristic rises with a corresponding slope, there will be at each value of the speed one particular resistance at which the current will have the critical value; and the higher the speed the higher may be the resistance. There is no such thing as a critical resistance *per se*: for whether a resistance is critical or not depends upon the speed. *Neither is there any such thing* per se *as a critical speed for a series dynamo;* for whether the speed is critical or not, depends on the resistance of the circuit.

CHARACTERISTIC OF SHUNT DYNAMO.

For the shunt dynamo there are two separate characteristics; the *external characteristic*, in which the quantities plotted are the amperes of current in the external circuit and the volts of potential between terminals; and the *internal characteristic* in which the volts and amperes of the shunt circuit are plotted. The internal characteristic of the shunt dynamo is quite similar to the external characteristic of a series dynamo, and shows the saturation of the field-magnets. It is better to plot it with ampere-turns instead of amperes, because the magnetization depends on the number of turns in the coil as well as the amperes.

The external characteristic of a small shunt dynamo (the same described by the late Sir William Siemens before

the Royal Society in 1880, and by Mr. Alexander Siemens in the *Journ. Soc. Teleg. Eng.*, March 1880) is given in Fig. 136, and the horse-power lines are shown dotted. The utmost power of this machine at 630 revolutions was just under 2 horse-power with a current of 30 amperes, and an electromotive force of 47·5 volts.

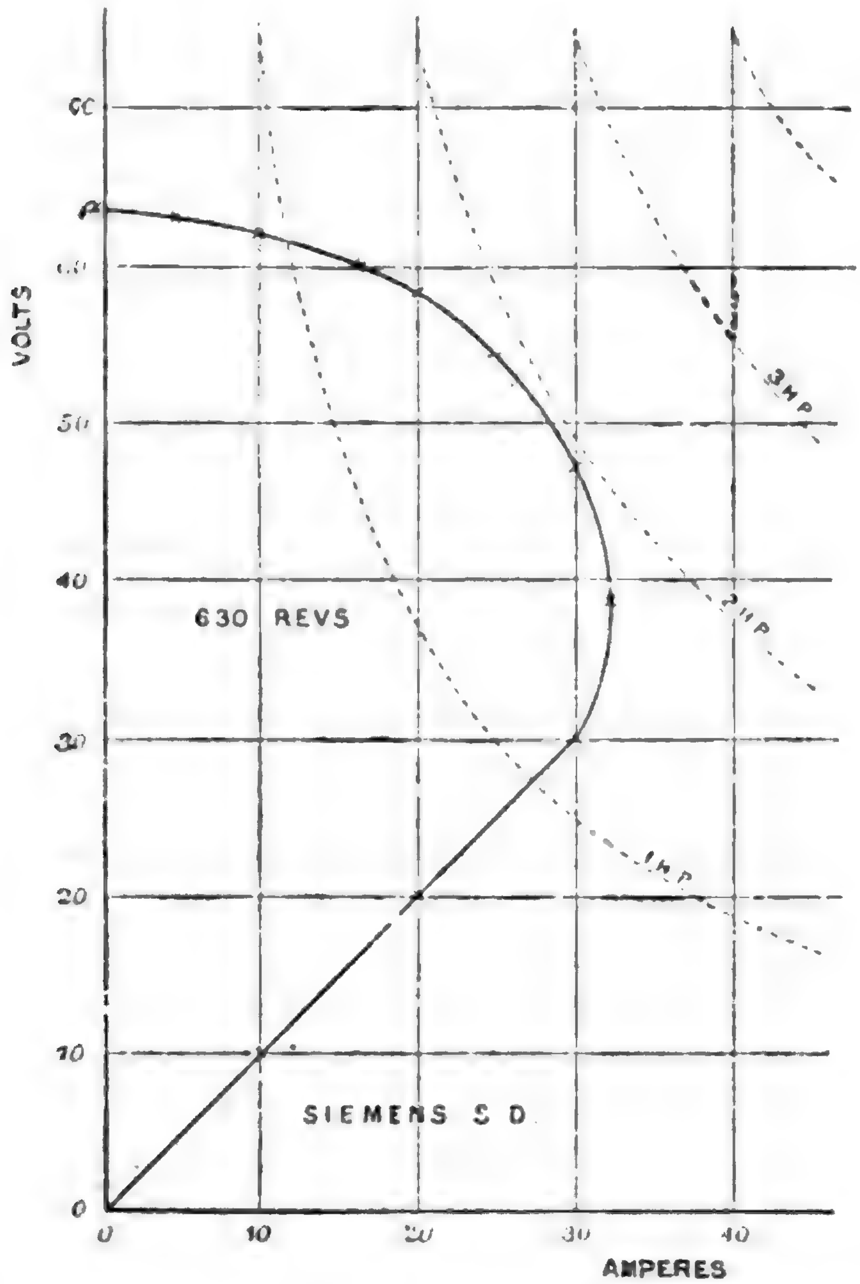


FIG. 136.—EXTERNAL CHARACTERISTIC OF SHUNT DYNAMO.

The curve of the shunt dynamo is curiously different from that of the series dynamo. It begins, on open circuit, at a point (marked *e*) where the volts are a maximum and runs slightly descending from the horizontal: then descends rapidly and returns toward the origin in a nearly straight line

The straight portion represents the unstable state when the shunt current is less than its true critical value. The critical external current, if it can be so called, is in Fig. 136 about 30 amperes. The slope of the line which constitutes the last portion of the characteristic represents the resistance which for the particular speed may be termed the critical resistance, and in this case is about 1 ohm. Any less resistance will cause the magnets to lose their magnetism at once. Any greater resistance will at once run the electromotive-force up above the critical value—in this case about 30 or 31 volts. If the resistance of the external circuit becomes in the least degree altered, the electromotive-force and current will alter enormously. If the resistance be steadily increased (and the

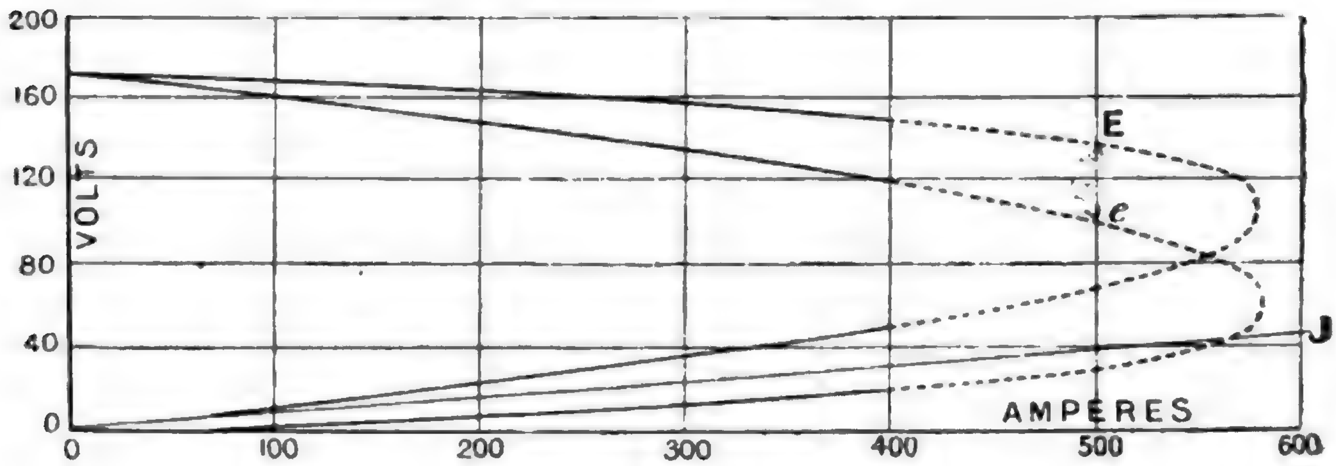


FIG. 137.—CHARACTERISTIC OF A SHUNT DYNAMO.

slope of the line from O to the curve be increased in steepness) the volts will go on steadily augmenting, and become a maximum when the external resistance is infinite, that is to say when the circuit is completely opened and the shunt coils receive the whole of the electromotive-force of the armature. Fig. 137 depicts the characteristic of a shunt-wound Gramme dynamo capable of giving 400 amperes. In this case the curve *e* represents the external characteristic, from which the curve E is calculated by adding to the ordinates portions equal to $r_a\ C_a$. As the conductors of the armature could not safely carry more than 400 amperes, the dotted portion of the curve represents results not actually observed. It is instructive to contrast the characteristic of the shunt dynamo with that of the series dynamo (Fig. 127). In the series dynamo, the

first part of the characteristic is a sloping line, and the tangent of the angle of its slope is also the critical resistance for the given speed. But the series dynamo will only work if the resistance of the external circuit is *less* than the critical value, and the shunt dynamo will only work if the external resistance is *greater* than the critical value. The contrast is even better shown by drawing a couple of curves in the two cases — not characteristics — showing the relation between the potential at terminals and the resistances of the external circuit. Fig. 138 shows this for a series machine, and Fig. 139 for a shunt machine. The electromotive-force of

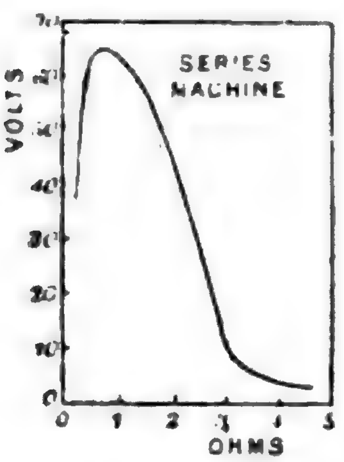


FIG. 138.

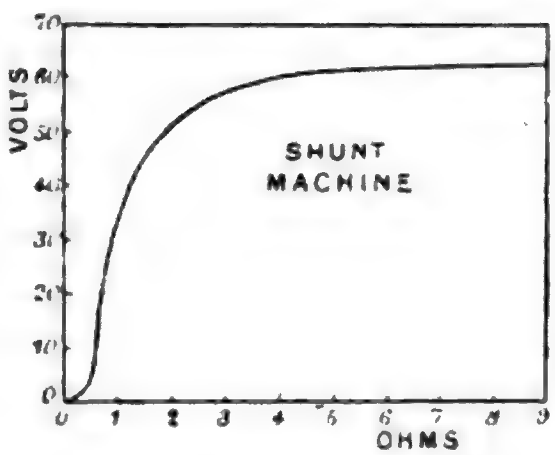


FIG. 139.

the one drops suddenly when the resistance exceeds 2 ohms; that of the other rises suddenly when the resistance attains the value of 1 ohm.

In the shunt dynamo the characteristic for a double speed cannot be obtained as in a series dynamo by doubling the heights of the ordinates. For even if at a double speed we adjust the external resistances so that the external current is the same as before, we do not get a double electromotive-force because we do not get the same current as before round the shunt-magnet circuit. And if, on the other hand, we adjust resistances so that we get the same shunt current as before, and therefore a double electromotive-force, we do not get the same external current as before. If, however, we alter the external resistance, taking a larger current externally, so as to reduce the shunt current to its former value, the magnetization will remain as before. In that case the double speed will produce very nearly a double electromotive-force,

but the shunt potential may remain as before, the external current being nearly doubled. This is shown in Fig. 140, where *e a* represents the external current in the first case, and *e* A the external current in the second. O A remains a straight line, but at this higher speed the slope is less. From this latter circumstance it may be foreseen that at higher speeds the resistance may be reduced to a lower value before the critical state is reached at which the machine "unbuilds" itself, *i.e.* discharges the magnetism from its field-magnets.

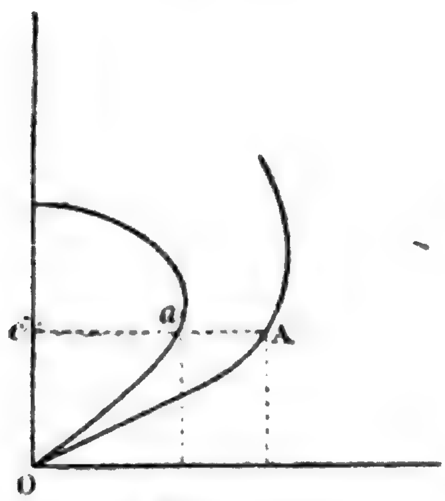


FIG. 140.

Curve of Total Current in Armature.—In the shunt dynamo the current in the armature is equal to the sum of the currents in the external circuit and in the shunt circuit; or

$$C_a = C + C_s.$$

A curve showing the relation between C and *e* is easily obtained. In Fig. 141 let the curve O *m i* be the "external

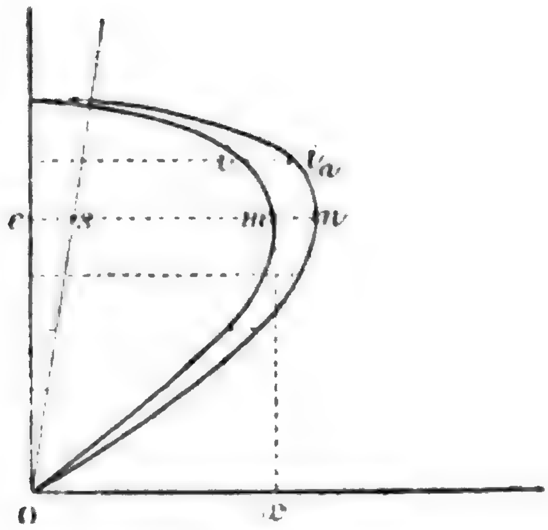


FIG. 141.

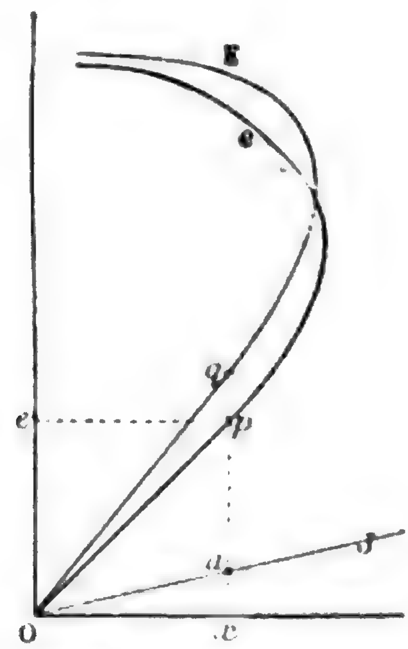


FIG. 142.

characteristic" at the given speed. Take any point on it such as *m*; at that point the potential between terminals is

measured by the length of $x\,m$ or O e, and the current in amperes is measured by the length O x or $e\,m$. Now draw the line s O at such an angle s O x that its tangent is equal to the resistance of the shunt. Then $e\,s$ represents the current that will run through the shunt when the potential is O e volts. Add on to the end of $e\,m$ a piece $m\,n$ equal to $e\,s$; then the whole line $e\,n$ represents the armature current C_a when the potential has the value O e. A set of similar points may be found giving the new curve O $n\,i_a$ required.

Total Characteristic of Shunt Dynamo.—If the total electromotive-force E and the total current C_a be plotted out, we shall obtain the characteristic of the total electrical activity of the dynamo.

Draw, as in the preceding case, the curve for e and C_a. Let p be any point on the curve where the potential is $p\,x$ or O e and the current $e\,p$ or O x. Then draw a line O J at such an angle a O x that its tangent is equal to the resistance of the armature. Call the point where this cuts $p\,x$, a. Then $a\,x$ represents the number of volts required to drive the current O x through the armature resistance. Add a piece $q\,p$ equal to $a\,x$ to the summit of the line $p\,x$. Then the height $q\,x$ represents the total electromotive-force E when the current C_a has the value represented by O x.

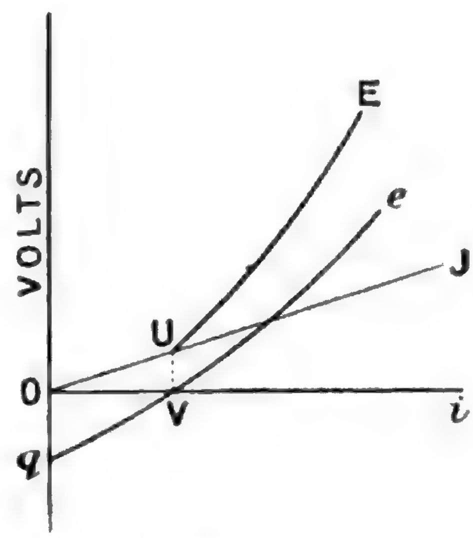


Fig. 143.

Characteristic of Shunt Dynamo, with Permanent Magnetism.—If there is residual magnetism in the field-magnets, there will be an electromotive-force induced, even before the shunt circuit is closed. In this case the characteristic would begin at a point p, a short distance along the horizontal axis. In fact the machine behaves as though there were already at work some small electromotive-force (not to be plotted), which had the effect of setting up already a current through the machine, so that the machine excites itself up with currents that are, in the early (and unstable) stages of the magnetiza-

tion, proportional to the ampere-turns going round the shunt circuit, *plus* some imaginary ampere-turns causing the permanent magnetism. If there is on the field-magnet a second coil, by which an independent magnetization can be introduced, the same kind of result will follow: the characteristic will begin at some point, such as V, the electromotive-force due to the ampere-turns in the shunt being plotted out above O, whilst the length O q below represents the part of the electromotive-force due to the ampere-turns (real or imaginary)

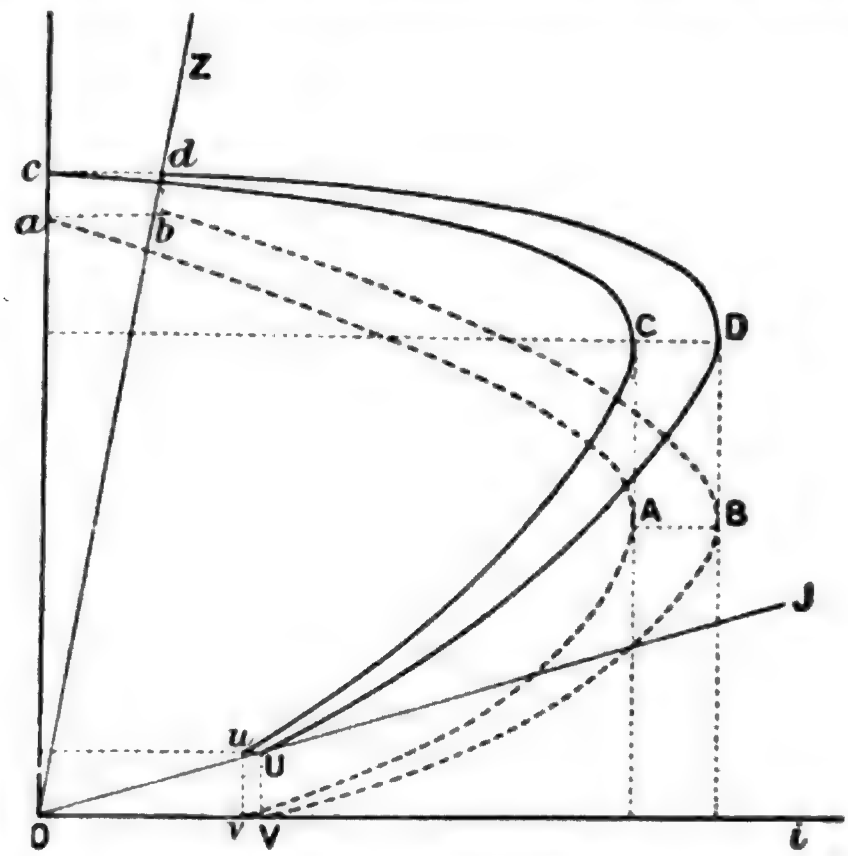


FIG. 144.—FOUR CURVES OF A SHUNT DYNAMO.

of the independent magnetism; and O V represents the current which the machine will give when short circuited.

There will, in fact, be four curves for a shunt dynamo, namely, those in which the quantities plotted out are respectively e and C, e and C_a, E and C, E and C_a. Of these, the first is the *external characteristic*, and the fourth the *total characteristic*.

These four are depicted in Fig. 144, where they are named A, B, C and D respectively. If D is given, A can be obtained in the following way:—Let the lines O J and O Z represent respectively by their slope the resistance of the armature and

of the shunt circuit. The curve B is got from D by deducting from the ordinates lengths equal to the portions of ordinates intercepted by the line O J; and curve C is got from curve D by deducting from the abscissæ lengths equal to the portion of the abscissæ intercepted by the line O Z. Then curve A is got by taking ordinates from B and abscissæ from C corresponding to any point on D.

It may be noticed that whilst D B represents the lost volts due to internal resistance of armature, C D represents the lost amperes which go round the field-magnets. The lower the resistance of the armature, and the higher the resistance of the shunt, the less will these losses be. In fact, with a well-built modern machine the four curves lie very close together.

If the curve of magnetization of the machine is known it is easy to determine the characteristic by a geometrical construction. The curve of magnetization O P M (Fig. 145) will show the relation

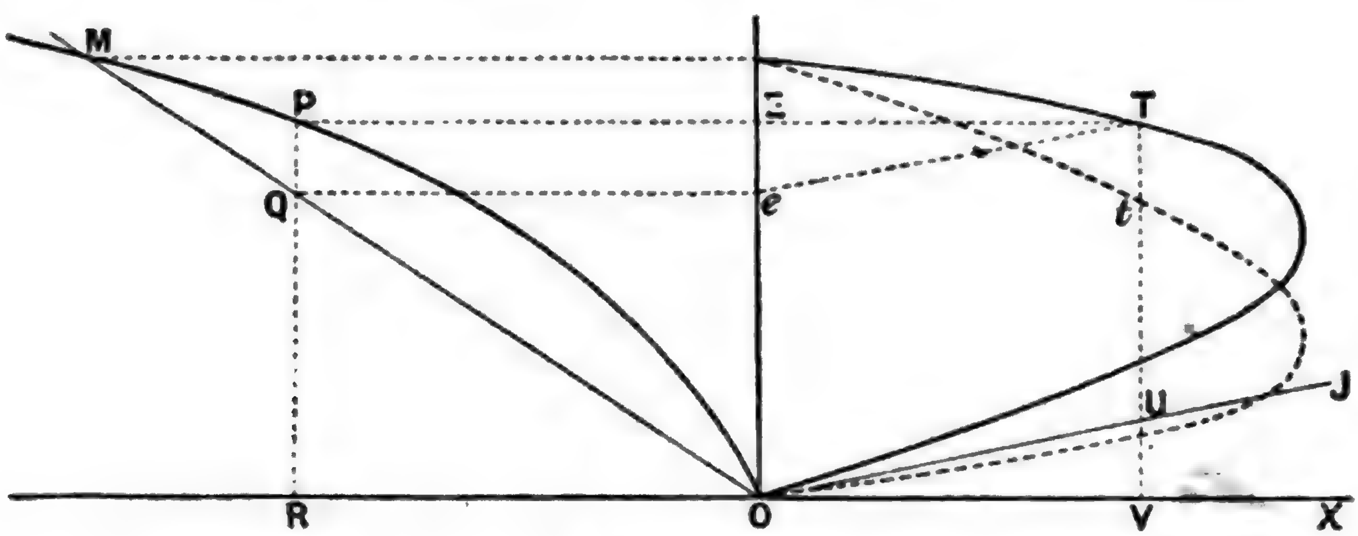


Fig. 145.

between N and the ampere-turns in the shunt coil, S, C, in our notation.

Let this curve be set out to the left of the vertical axis, then the line O R may be divided out either in a scale representing ampere-turns or in a scale representing amperes, S, divisions of the former scale corresponding to one of the latter scale. The vertical scale plotted out along O E may in like manner represent either N or E; $n\,C \times 10^{-8}$ being the ratio of the readings of the scales. Now set out the line O M, making with O R an angle such that the tangent of its slope corresponds, in the units chosen, to the resistance of the

shunt-winding; for example, if the shunt-resistance be 16, the line will pass through a point the ordinate of which represents 16 volts and the abscissa 1 ampere. Let this line meet the curve of magnetization at M. If we consider any point P on the curve, its ordinate P R will represent, according as we please, either the effective magnetism when the magnetizing current is O R, or the whole number of volts E induced in the armature; and the part of the ordinate Q R will represent the difference of potential e. Clearly then P Q will represent $E - e$, that is to say, the volts lost in the armature, which are equal to $r_a C_a$. Now, if on the right of the diagram we lay out a line O J at such an angle that the tangent of its slope represents the armature resistance r_a, then if V be taken so far along the horizontal axis that V U = P Q, the length O V will represent C_a. The most convenient construction is to project points

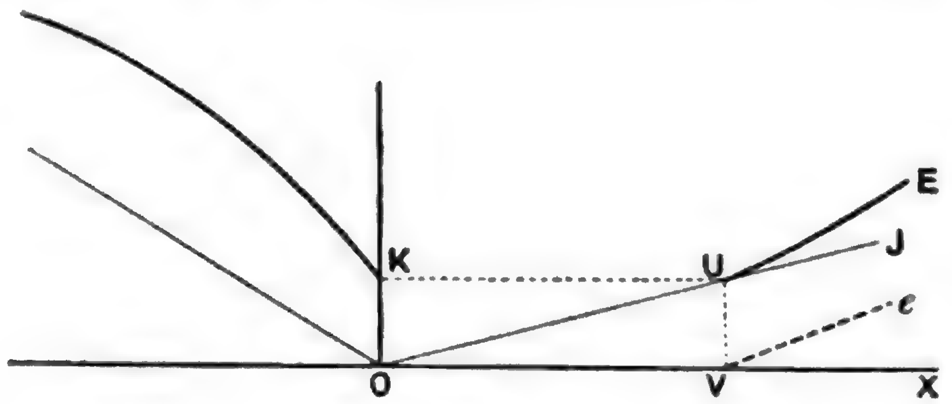


Fig. 146.

P and Q across to E and e, and from e draw e T, parallel to O U, meeting E T in T; then drop a perpendicular from T giving the points t, U and V, where T t = U V. T will be a point on the curve connecting E and C_a; t a point on the curve connecting e and C_a. From the latter curve the external characteristic can be got as shown on p. 215. Of these hyperbolic curves the lower limb which returns towards O represents the unstable portion corresponding to the lower part of the magnetic curve. From the existence in the curves of a maximum value of C_a, where the curve turns round on the extreme right, it must not be inferred that the machine can yield this maximum current; on the contrary, the maximum current that the machine can safely give depends on the section of its armature wires, and these are—in the best machines—not intended to carry the current under such conditions. The working part of the curve is usually the top part (Fig. 145), and it will be obvious from the construction that the smaller the internal resistance, the further will the curve extend to

the right and the more nearly horizontal will the tops of both curves be; a good shunt-dynamo, with very little internal resistance, being *nearly* self-regulating for constant potential.

If there be no initial or residual magnetization, the curves will both pass through O; but neither of them will do so if there is initial or residual magnetization. In that case the curve of magnetization will commence above O at some point such as K, Fig. 146, and the lower ends of the two curves for E and e will end at points so far to the right that the width U V = K O. With almost every shunt dynamo it is found that if descending values of e are taken (at any given speed) e becomes zero, whilst C has still a definite value.

It will also be noticed that the limiting value of e depends on the slope of M O, that is to say, on the resistance per turn of the shunt coil; any diminution of the resistance per turn will raise E by forcing up to a higher degree the magnetization corresponding to a given value of e.

Contrast of Series Dynamo with Shunt Dynamo.—The difference between series dynamos and shunt dynamos in their behaviour when the resistance of the current is increased or decreased, has already been touched upon in p. 213. In electric lighting, dynamos are usually required either (a) to supply glow-lamps arranged in parallel, in which case the dynamos must maintain a constant potential at the mains, or else (b) to supply arc-lamps arranged in series, in which case the dynamo is required to yield a constant current. In the case where the potential is to be constant, the current will vary with the number of lamps in parallel; in the second case, where the current is to be constant, the electromotive-force must vary as the number of lamps in series.

To understand the applicability of series or shunt dynamos to either of these tasks, it will be convenient to construct (either from experiment or from theory) comparative curves. In the case of parallel distribution, every additional lamp switched on across the mains adds to the conductance of the circuit an amount equal to its own conductance (*i.e.* equal to the reciprocal of its own resistance). It is therefore expedient to plot out together the values of e and of $\frac{1}{R}$. This has been

done in Fig. 147 for two dynamos, for each of which the maximum value of e was the same. It will be seen that for neither a series nor for a shunt machine does the value of e remain constant as the number of lamps across the mains is increased. The shunt machine gives the more nearly constant potential, but falls off as the number of lamps is increased.

In the case of single-circuit distribution to lamps in series, every additional lamp adds to the resistance of the circuit, and in this case it is expedient to plot out together the values of C and R. Fig. 148 shows the result for the two kinds of machine. It will be seen that neither machine gives anything like a constant current; but for the shunt machine there is just one brief

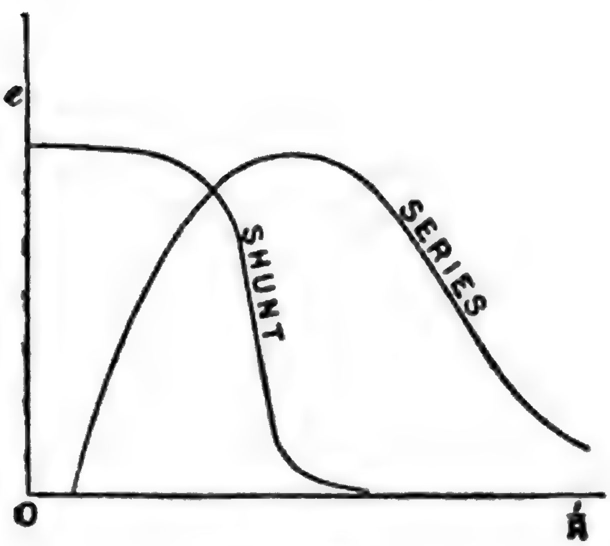


FIG. 147.

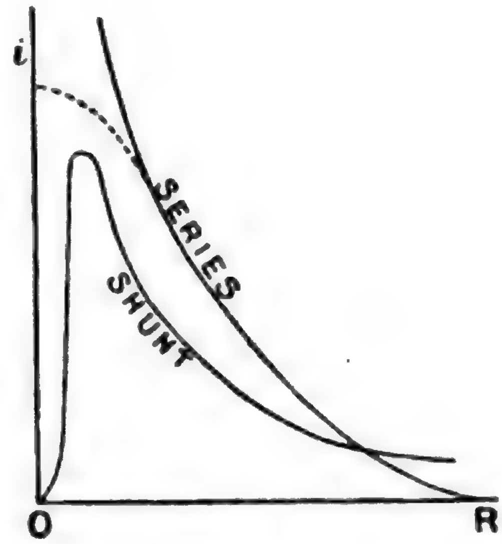


FIG. 148.

stage, namely, when its current is at the maximum, where the value is more constant than anything that the series dynamo can give. The dotted part of the curve corresponds to the case of a series dynamo so designed as to have a drooping characteristic (like Fig. 131, p. 205), which gives more nearly (with moderately small resistances) a constant current. But it is abundantly clear that something more than a simple series or simple shunt machine is requisite to give a real self-regulating machine for either purpose.

Further use of characteristics.—The following examples of the further use of characteristics are taken from Dr. Hopkinson's paper in the *Proc. Inst Mech. Engineers* for April 1880.

Relation of Characteristic to Size of Machine.—Suppose that a certain dynamo of a given construction has for its characteristic the curve O *a* (Fig. 149). What will be the characteristic of a dynamo built of precisely the same type, but with all its linear dimensions doubled? The surfaces will be four times as great, the volume and weight eight times as great. There will be the same number of turns of wire, but the length will be doubled and the cross-section quadrupled, and therefore the internal resistances will be halved. If the resistances were adjusted so as to give the same current as before, the new machine would have only half the intensity of field of the small one. But if adjusted to give the same intensity of field as before, the current will be doubled.

Now the magnetic flux will be increased fourfold, and therefore the electromotive-force will be four times as great. But we only wanted the current doubled. That is to say, the resistance will have to be doubled if the field is to be of the same intensity. To represent this state of things, take the point *a* on the characteristic of the small machine, and draw the ordinate *a m*. Draw O M, double O *m*, and at M erect an ordinate A M four times the length of *a m*. The resistance—the slope of O A—is double that of O *a*. The new characteristic will pass through A. The points *a* and A are similar points with respect to the saturation of the iron of the magnets; and it is this which determines the practical limits to the economic working of a dynamo of given type at a given speed. Hence we see, with quadrupled electromotive-force and double current, the output will be eight times as great as with the smaller machine when worked up to an equal saturation limit. These points may be compared with the discussion of the relation of size to efficiency on p. 108.

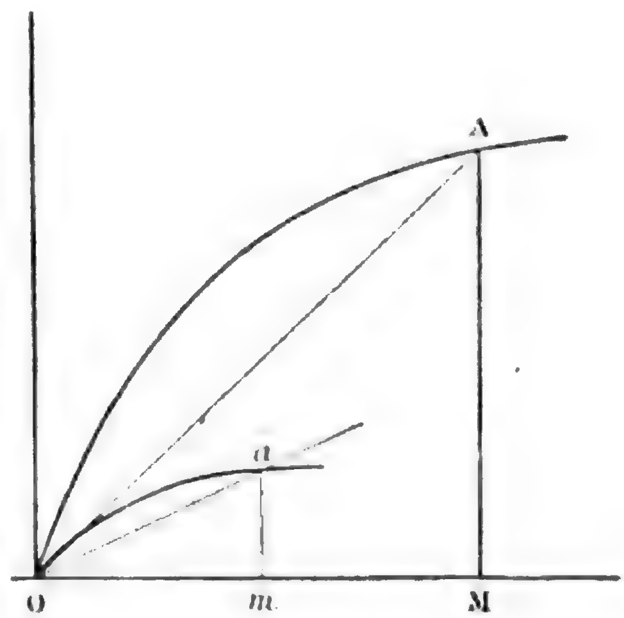


Fig. 149.

Application of Characteristics to Dynamos used in Charging Accumulators.—The following problem is of great practical importance :—*Suppose a dynamo is used for charging an accumulator, and is driven at a given speed, what current will pass through it?*

Dr. Hopkinson has given a solution of this problem for the case of a series dynamo. Draw the total characteristic of the dynamo (Fig. 150) for the given speed. Along O Y set off O E to represent the electromotive-force of the accumulator, and through E draw the line C E A, making an angle with O X such that its tangent represents the resistance of the whole circuit, including the accumulators. This line will cut the charac-

teristic in the points B and A ; and, if the characteristic be repeated backwards, in C also. This negative branch of the characteristic is simply the characteristic of the dynamo when the current through it is reversed, and

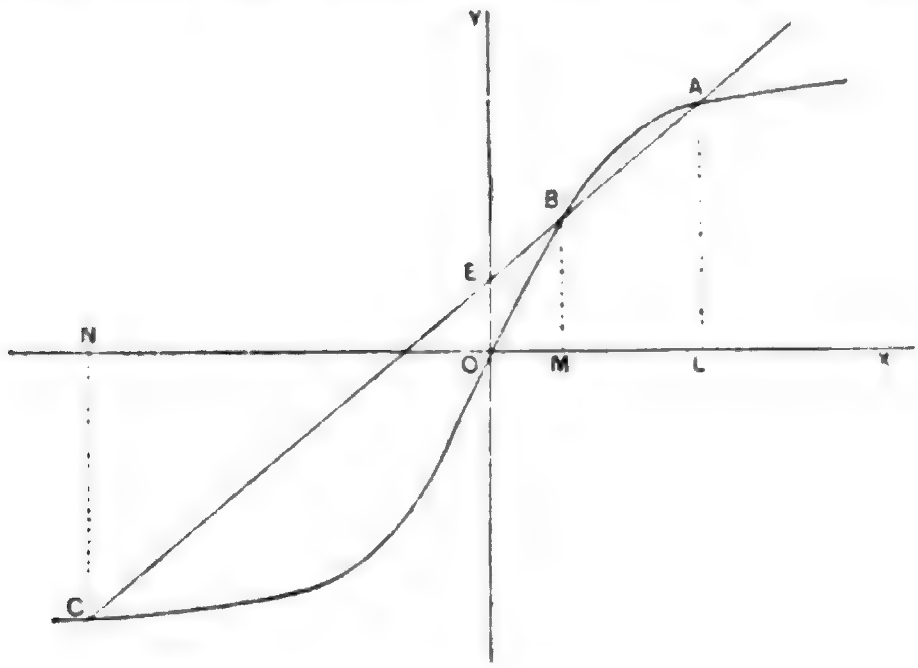


FIG. 150.

its electromotive-force therefore also inverted. Then O L represents the actual current in the circuit; O M represents an unstable current which might exist for a moment; and O N represents the current which would traverse the circuit were the accumulators to overpower the dynamo and reverse it, as indeed frequently happens when series dynamos are so used. For it will be observed that if, as is the case when accumulators are reaching their full charge, their electromotive-force were to rise, or the resistance of the circuit to increase, the inevitable result would be to diminish the current O L, so that the magnetism of the field-magnets will also drop, thus diminishing the effective electromotive-force of the dynamo: and consequently the point A will be brought nearer to the position of instability at the bow of the curve.

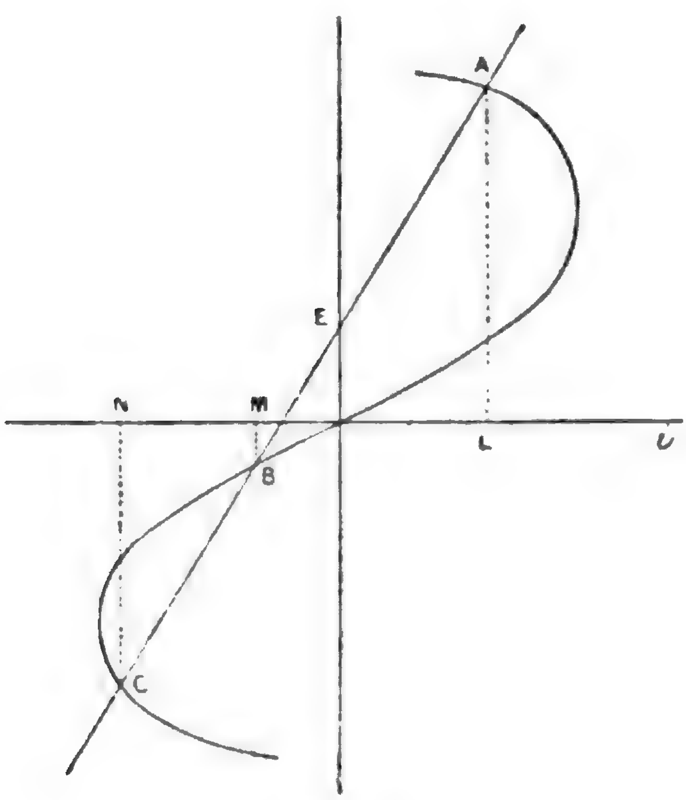


FIG. 151.

With the shunt dynamo the case is different. Let Fig. 151 represent the characteristic of the shunt dynamo, the external current being plotted

along O X, and the total electromotive-force along O Y. Draw the line C E A as before. Then it cuts the positive branch at A, and O L is the current in the main circuit. If, now, either the counter electromotive-force of the accumulators or the resistance of the circuit increases, the effect will be to move the point A to a higher point on the curve. The charging current O L may diminish, but the shunt current will increase or the effective electromotive-force A L will be increased. Therefore with the shunt dynamo there will be no likelihood of the accumulators overpowering and reversing the dynamo.

In the case of a series dynamo driving an arc-lamp, Fig. 150 also may be applied to explain the instability sometimes observed. The arc acts as though it had a counter electromotive-force, which, for steady arcs is not less than 35 volts. Hence if O E is set off to this value, the resistance of the rest of the circuit must be low enough for the sloping line E A to cut the curve above the "knee," otherwise the condition becomes unstable.

CHAPTER XI.

CONSTANT POTENTIAL DYNAMOS.

Conditions of Supply.—For some purposes—as for feeding a system of incandescent lamps in parallel—the current must be supplied from the mains at an absolutely *constant potential* or *pressure;* that is to say, the difference of potentials between the mains must be constant. This, of course, implies that the current delivered by the machine shall vary exactly in a ratio inverse to that of the resistance of the external circuit; increasing, as the resistance is diminished by adding to the number of lamps across the mains of the circuit. But we have seen that, owing to two causes—(1) internal resistance, (2) demagnetizing reactions of armature—the volts at the terminals at full load fall short of the value they would have (at the same speed and magnetization) at zero load. The *lost volts* increase with the load. Hence, means must be taken to compensate for the lost volts if the supply is to be maintained *at a constant pressure.* If a dynamo is to supply lamps at, say 100 volts, the pressure must not be allowed to fall to 97 or 96 volts when all the lamps are at work.

For some other purposes, as for supplying a set of lamps connected in a simple series, placed on one line, it is necessary to maintain in the line an absolutely *constant current*, no matter how many or how few lamps or motors may be at work. This, of course, means that when the resistance of the main circuit is increased by the switching-in of more lamps, the dynamo must put forth a proportionate increase of electromotive-force.

The two ends to be attained by regulation are therefore not only distinct, but incompatible with one another; a dynamo cannot possibly keep its electromotive-force constant, and at

the same time vary it in proportion to the varying resistance of the external circuit. The two systems are adapted to entirely different cases of electric distribution. Their theory is different; and the practical modes for carrying them out are different also.

Constant-current machines, as required for arc-lighting, and for glow-lamps in series, are described in Chapter XVIII. The present chapter will deal only with machines for supply at constant pressure.

There are various ways of governing dynamos so as to maintain either a constant potential or a constant current. Some of these methods involve hand regulation; others, automatic switching in or out of resistances, to vary the excitation of the field-magnets; others, automatic adjustment of the brushes; and others, electrical governing of the speed. The chapter on Regulators deals with these. Let it be noted in the first place that the voltage of a given dynamo depends, as shown by the fundamental equation (p. 170), on three things—the speed, the number of armature-windings, and the magnetic flux: hence it follows that any one of these might be used to control the output of the machine. The speed can be changed by purely mechanical contrivances. The number of effective armature conductors can be changed by shifting the brushes forward beyond the neutral point. The magnetic flux can be varied by altering the magnetizing current that excites the magnetism, or by changing the disposition of the magnetic circuit.

In cases of isolated plant it may be convenient to apply a governor to so vary the speed in accordance with the demands on the circuit as to maintain a constant electric pressure; but this is not satisfactory when the engine has other work than driving a single dynamo. Those methods have been preferred which admit of the maintenance of a constant speed of driving. Throughout this chapter this condition will be assumed to hold good; and as a purely magnetic method of regulation is but little used we need only deal here with the methods that depend on varying the excitation of the magnets.

Hand Regulator.—In Edison's method of supplying mains at a constant potential a shunt dynamo is employed, a variable resistance, or rheostat, R, being introduced into the shunt-circuit (Fig. 152). A lever moved by hand, whenever the potential rises or falls below its proper value, makes contact on a number of studs connected with a set of resistances, and thus controls the degree of excitation of the field-magnets. To make the arrangement automatic the variable resistance should be adjusted by an electromagnet the coils of which are an independent shunt across the mains. The shunt dynamo, if well constructed, is, as shown on p. 212, nearly constant

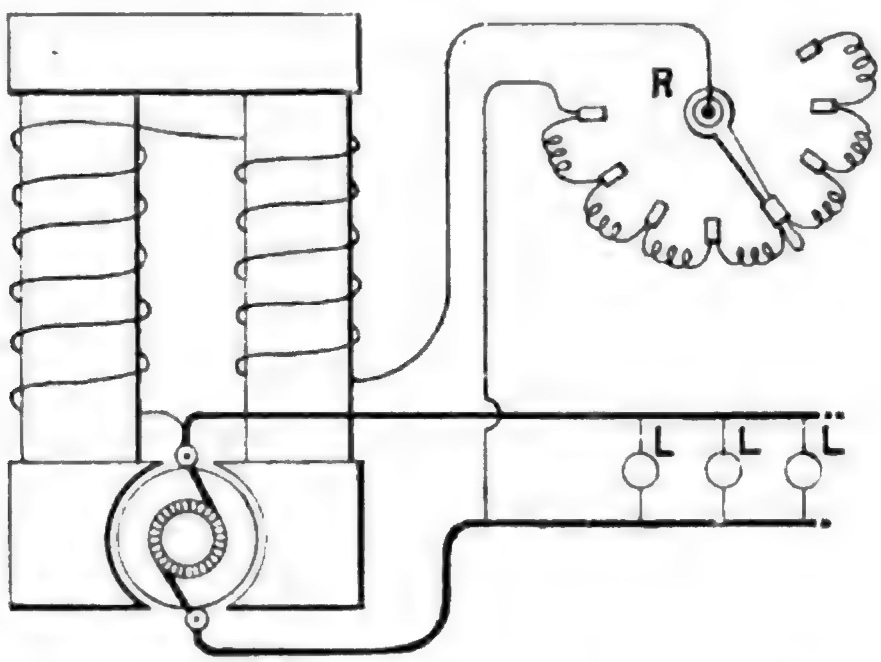


FIG. 152.—EDISON'S METHOD OF REGULATING.

in its voltage; the pressure at the terminals falls off very little at full load. With such a dynamo, but a small increase of exciting power is needed to make up for the lost volts at full load. The regulating rheostat is equally applicable to a separately-excited machine.

Self-regulating Machines.—The theory of self-regulation is extremely simple. Volts depend on the flux; hence, any drop in the volts can be compensated by increasing the flux. The problem then is how to make the main current, which as it increases causes the volts to drop automatically, increase the flux. It is clear that a compensating main-circuit coil of sufficient turns to predrce the needed *additional* excitation,

must be wound upon the field-magnet. The compensating coil must obviously be thick enough to carry the main current, and usually consists of few turns. If the machine is shunt-wound to begin with, and a compensating coil in series with the armature is thus added, the combination is usually termed a "compound" winding. The term "compound dynamo" was introduced by Messrs. Crompton and Kapp to signify a dynamo with mixed series and shunt-winding, by analogy with the engineers' term "compound engine" for a steam-engine working with both high- and low-pressure cylinders. A compensating series-coil is, however, equally applicable to any well-designed dynamo in which the initial magnetism is independently excited. The following combinations are possible:—

(*i.*) Series regulating coils + permanent magnets to excite the field initially with an independent constant magnetization.

(*ii.*) Series regulating coils + an independent current circulating in separate coils round the field-magnets, to produce an independent constant magnetization.

(*iii.*) Series regulating coils + an independent current circulating in the main circuit (and generated either by a battery or by an independent magneto-dynamo) having the effect of partly exciting the field-magnets with an independent constant magnetization.

(*iv.*) Series regulating coils + shunt-magnet coils supplied by a portion of the current of the machine itself, thereby partly exciting the field-magnets, with an independent and nearly constant magnetization.

(*v.*) Alternate-current dynamos may be compounded by providing them with regulating coils supplied with a current derived (by a suitable transformer) from the main-circuit current, and proportional to it; the derived currents being first sent through a rectifying commutator. The independent magnetization may be derived either from an auxiliary exciter, or from a separate coil or group of coils in the armature, or, in fact, by another transformer, the primary of which is placed across the mains as a shunt; in either of the latter cases the current being properly commuted.

Theoretically, several other self-regulating combinations are possible; for example, a machine with a long armature lying between two separate field-magnets, one independently excited, the other in series; a series machine with unsaturated magnets combined with a (quasi-independent) series machine with over-saturated magnets on the same shaft; a series machine having two sets of field-magnet poles at different leads, one of the sets of poles being the series-excited set, the other excited independently, or in shunt circuit, &c.

THEORY OF SELF-REGULATION.

In considering the theory of self-regulation we shall proceed as follows:—First find an expression for the pressure at the mains. This will, in general, consist of three terms. Secondly, we shall consider these three terms as to whether their factors are constants or variables. Then, having ascertained which of the terms contain variable factors, we must consider what conditions must be laid down (such as prescribing a particular speed or a particular number of windings) in order that the terms containing variable factors shall disappear. These conditions will be embodied in an "equation of condition," which will be then discussed. In general it will be found that if the speed is prescribed beforehand, there will be a certain "critical" number of regulating coils to be deduced; or, on the other hand, if the number of regulating coils is prescribed beforehand, there will be a particular or "critical" speed at which self-regulation holds good.

It is possible to treat the theory either algebraically or geometrically. Both methods will be here used.

Case (i.). Series Regulating Coils + Permanent Magnets (compare p. 55).—If the field-magnets are partly permanently magnetized, or if there are permanent steel magnets in addition to the electromagnets, giving an initial field, we may denominate the initial flux as N_1.

Now the fundamental equation of the series dynamo is

$$\mathrm{E} = n\,\mathrm{Z}\,\mathsf{N},$$

and the difference of potential or pressure at the terminals is found by deducting the lost volts; or

$$e = \text{E} - (r_a + r_m)\,\text{C}.$$

But N, the number of magnetic lines that pass through the armature at any instant, is made up of two parts, the permanent independent part N_1, and a part depending upon the current C, and equal to

$$\frac{4\,\pi\,\text{S}_m\,\text{C} \div 10}{\Sigma\,\frac{l}{\mu\,\text{A}}};$$

where S_m is the number of turns in the compensating coil, l the length of the magnetic circuit, A its cross section, and μ the *average* value of the permeability (see p. 120) between the two extreme values that it has when C is zero and when C is at its maximum. If for brevity we write

$$\frac{4\,\pi}{10}\Big/\Sigma\,\frac{l}{\mu\,\text{A}} = q,$$

we may then write the variable part of N as $q\,\text{S}_m\,\text{C}$; and therefore,

$$\text{N} = \text{N}_1 + q\,\text{S}_m\,\text{C};$$

and we get, as the complete expression for e,

$$e = n\,\text{Z}\,(\text{N}_1 + q\,\text{S}_m\,\text{C}) - (r_a + r_m)\,\text{C},$$

or

$$e = n\,\text{Z}\,\text{N}_1 + n\,\text{Z}\,q\,\text{S}_m\,\text{C} - (r_a + r_m)\,\text{C}.$$

The expression on the right-hand side of this equation consists of three terms, of which the first contains the speed and two constants as factors. The last two contain a variable, the current, and one of them also contains as factors the speed n and the number of regulating coils S_m. If S_m is prescribed beforehand, then the particular speed at which the dynamo is self-regulating will be clearly that speed at which the expression for e will contain nothing but constants. If n is prescribed beforehand, then we must vary S_m so as to eliminate

the terms that contain the variable factor. Since the two last terms are of opposite sign, it is clear that by varying S_m or n, or both, the value of $n Z q S_m$ may be made numerically equal to $r_a + r_m$. Then at the constant speed, which we will call n_1, the last two terms will cancel one another out, or,

$$n_1 Z q S_m C - (r_a + r_m) C = 0.$$

That is to say, S_m and n_1 must be such that

$$n_1 Z q S_m = r_a + r_m. \qquad \text{[XIII.]}$$

This is the equation of condition.

If the condition laid down in this equation is observed, then the last two terms for e disappear, and we have simply,

$$e = n_1 Z N_1 = a \textit{ constant.}$$

Having thus proved that, at the given speed, e is a constant, it is worth while to inquire what it is that determines the value of e. Clearly e is directly proportional to N_1, the initial flux. Therefore, we can arrange that the dynamo, still driven at the given speed, shall give any pressure we please, within limits, provided we alter N_1 in the requisite proportion.

Suppose that the speed is prescribed by mechanical considerations, then the proper or critical number of regulating coils is given by the expression

$$S_m = \frac{r_a + r_m}{n_1 Z q}. \qquad \text{[XIV.]}$$

This is instructive. The higher the internal resistance of a dynamo the greater must be the number of the regulating coils in series, if it is to be self-regulating.

Returning to the equation of condition, we will write it in the second form—

$$n_1 Z q S_m = r_a + r_m,$$

which for a given number of series coils gives us as the value of the critical speed,

$$n_1 = \frac{r_a + r_m}{S_m} \cdot \frac{1}{Z q},$$

and this speed will be higher the greater the internal resistances are.

Lastly, we may write the last equation in the following way,

$$\text{critical speed} = \frac{\text{total internal resistance}}{\text{number of turns of series coils}} \times \text{a quantity}$$

depending only on the armature windings and on the magnetic circuit and its working permeability within the range for which regulation is required.

So far we have assumed that the only cause of drop of pressure that needed to be compensated for was that due to internal resistances. But the drop of pressure due to the demagnetizing action of the armature is in modern machines a consideration of even more importance. To take account of this action we must remember that if the angle of lead λ is known, the demagnetizing belt of conductors (see p. 85) will be that comprised within an angle of $2\ \lambda$, namely $Z\ \frac{\lambda}{180^\circ}$. And each such conductor carries $\frac{1}{2}$ C amperes, making the demagnetizing ampere-turns $Z\ \lambda\ C \div 360^\circ$. Or, if the number of armature conductors within the angle λ is called D, the demagnetizing ampere-turns will be $2\ D \times \frac{1}{2}\ C = D\ C$. As, however, these turns are situated over the armature, whilst the compensating coils are wound on the field-magnet, their number will need to be greater in proportion approximately to the leakage coefficient v (see pp. 148 and 346). Hence we shall have to increase S_m, the series coils, from the value found above to the value

$$S_m = \frac{r_a + r_m}{n_1\ Z\ q} + D\ v. \qquad \text{[XV.]}$$

Case (ii.) Series Dynamo + Separately-excited Coils (see "*Series and Separate*," Fig. 44, p. 55).—In this case there is an initial magnetism due to a separate exciting current.

If we call the number of magnetic lines due to the independent excitation N_1, the same argument holds good as in the preceding case, and the same conclusions. N_1 will not, however, be really a constant, for the effect of the introduction of a constant amount of magnetizing force will vary with the degree of saturation resulting

from the *whole* magnetizing force. If, however, the average working permeability throughout the range of regulation is taken into account in the calculation of N_1 as well as in that of S, then any falling-off in the effect of the independent exciting current is implicitly provided for.

Geometrical Demonstration of Cases (i.) and (ii.).—On p. 185 it was shown how the values of the potential at terminals fall off in magneto and separately-excited dynamos as the current increases, e always being less than E by an amount equal to r_a C.

To represent the facts, let O X and O P be taken as the axes for plotting out amperes and volts, and let O P (Fig. 153) represent the electromotive-force ($E = n_1 Z \mathsf{N}_1$) due to the permanent or independent magnetism, as measured when no current is running through the armature. Now, assuming that the armature reactions are small enough to be neglected, E will at constant speed remain the same with all currents, but e will drop. From O set off the line O J at an angle such that its tangent represents the internal resistance of the machine. Now consider the case when the current C has the particular value corresponding

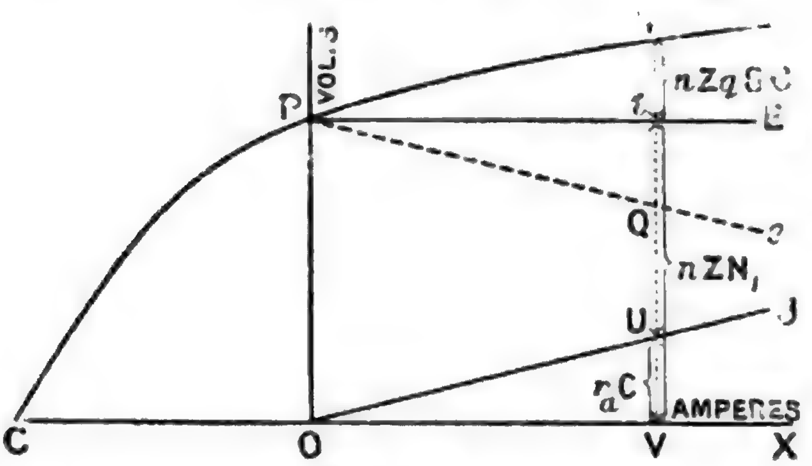


FIG. 153.

to the length O V. The height U V will be the drop in the external volts; for U V = tan U O V × O V = r_a C. Cut off from t V a portion, t Q = U V, and Q V will represent e. While the curve for E and C is approximately a horizontal line, the curve for e and C (the external characteristic) falls, as shown by the dotted line. Any point on the e curve can be got from the E curve by simply deducting from the height a piece equal to the corresponding width across the triangle J O X. Now it must be obvious that if when the E curve is horizontal the e curve slopes downward, we must use an E curve that slopes upward by a precisely equal amount, if we want to get a horizontal e curve; that is to say, if we want to get constant potential. How are we to get an upward sloping E curve? Remember that at a given speed, n_1, the value of E is $n_1 Z \mathsf{N}_1$, where N_1 means that the magnetic circuit has somehow (either permanently or by a separate current) been excited up to such a degree that N_1 lines go through

the armature. The same plotting that serves for volts will serve for values of N by choosing the appropriate scale; or, O P may represent N_1. Therefore P is a point on a curve of magnetization, which will rise still higher if only we put on more ampere-turns of excitation. Therefore all that is required to be done is to put on the magnets a coil in series, having such a number of turns S_m that the ampere-turns S_m C will have the effect of raising the magnetism in the right proportion; in fact, so that T t shall be equal to U V. We have now got an E curve which slopes up—not quite a straight line, to be sure, but such that when we subtract the volts required to drive the current through the armature resistance, we get an e curve that is approximately level.

Comparing the algebraic and geometric methods, we see that t V corresponds to $n_1 Z N_1$; T t to $n_1 Z q S_m C$; and U V to $r_a C$, or if the resistance of the added series coil is included in the slope of the line O J, U V will correspond to $(r_a + r_m)$ C.

Case (iii.) Series Dynamo + Independent Electromotive-force thrown into the Main Circuit.—This really comprises two cases: where the independent constant electromotive-force is due to a battery, and where it is due to a separate magneto machine driven at a constant speed ("Series and Magneto," see p. 55). The argument is the same, however, for both cases. Fig. 154 will represent either case.

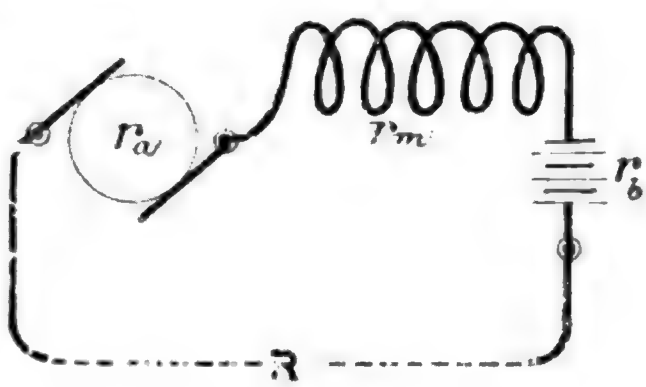


FIG. 154.

The solution is identical with the preceding cases, except that there are now three resistances internal to the arrangement to be compensated.

Case (iv.) Series Regulating Coils + Shunt Exciting Coils: "Compound Winding."—The compound-wound dynamo may be regarded as either a series dynamo to which some shunt windings have been added, so as to provide an initial magnetization, or as a shunt dynamo to which some series windings have been added to compensate for the drop of potential at the terminals. There are two possible methods of connecting the shunt coils to the dynamo, and the pro-

portions differ slightly in the two cases. In the "short-shunt" method (see p. 56) the shunt coils are joined as a shunt to the armature part of the dynamo only, being connected across from brush to brush. In the "long-shunt" method the shunt coils are connected across the terminals of the machine, and may, therefore, be regarded either as a shunt to the external circuit, or as a shunt to the armature and series coils together. In the former arrangement the current through the shunt is not constant, because though e may remain fairly constant, the potential at the brushes does not, but increases when the external circuit's resistance decreases. In the latter arrangement the current through the shunt is constant if e is constant, and the case becomes one analogous to those already discussed,

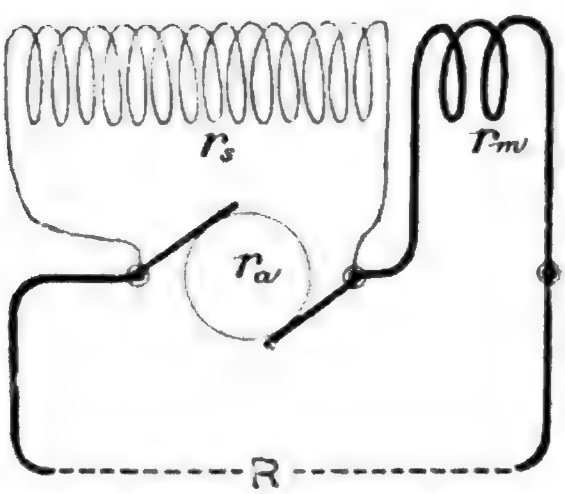


FIG. 155.

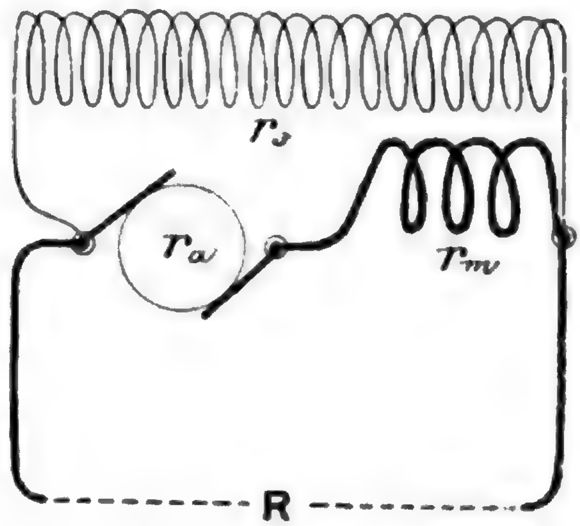


FIG. 156.

of an independent constant excitation. The connexions of the short-shunt method are indicated in Fig. 155. In a well-designed dynamo it makes very little difference whether the shunt is connected across the brushes or across the terminals of the main circuit. The connexions of the long-shunt arrangement are as shown in Fig. 156. The calculations for the two cases are practically identical, and involve the same kind of arguments. That for long-shunt is a little more simple, and is accordingly given.

We have then

$$E = n\,Z\,N \; ; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$e = E - (r_a + r_m)\,C, \quad . \quad . \quad . \quad . \quad (2)$$

and as the magnetism depends on the total number of ampere-turns of excitation, we shall write,

$$\mathsf{N} = q\,(\mathrm{S}_s\mathrm{C}_s + \mathrm{S}_m\mathrm{C}_a)\,; \quad . \quad . \quad . \quad . \quad (3)$$

where q has the same signification as before (p. 229), namely

$$= \frac{4\,\pi}{10}\ \Sigma\ \frac{l}{\mu\,\mathrm{A}}\,;$$

or more strictly is the variable number representing, at the various stages of magnetization, the numerical ratio between flux and excitation for the magnetic circuit of the particular dynamo. For the present purpose it is also necessary to consider the value which q has when the external current is zero, and when the only excitation is that due to the shunt: this may be called q_0. Then the initial flux on open circuit will be :—

$$\mathsf{N}_0 = q_0\,\mathrm{S}_s\mathrm{C}_s.$$

Then from the three equations we have

$$e = n\,\mathrm{Z}\,q\,\mathrm{S}_s\,\mathrm{C}_s + n\,\mathrm{Z}\,q\,\mathrm{S}_m\,\mathrm{C}_a - (r_a + r_m)\,\mathrm{C}_a.$$

Now here we have three terms, the first containing, as factors, the speed (which may be kept constant), and the shunt current C_s which will be made constant if e can be made constant; the second contains the speed also as a factor; the second and third both contain the variable current C_a. The two variable terms are of opposite sign. Now e cannot possibly be a constant, when two of its terms contain a variable as factor, unless the coefficients of that variable factor are such that they make those two terms cancel one another; e cannot be constant unless either the speed n or the windings S_m, or both, are so adjusted as to fulfil this. But these can be varied so that it is possible for the two coefficients to be equal, viz.—

$$n\,\mathrm{Z}\,q\,\mathrm{S}_m = r_a + r_m.$$

This is then one of the two equations of condition; and the critical number of series-turns at the given speed will be

$$\mathrm{S}_m = \frac{r_a + r_m}{n} \cdot \frac{1}{\mathrm{Z}\,q}\,.$$

Or, if S_m is prescribed, the critical speed will be

$$n = \frac{r_a + r_m}{S_m} \cdot \frac{1}{Zq}.$$

If this condition be observed, then e will be constant and have the value

$$e = n Z q S_s C_s.$$

But this would leave e indeterminate, since $C_s = e \div r_s$. But we may reflect that though this equation might not give us the value of e, there will nevertheless be a determinate value for it, namely, the same value that e would have when there is no current taken from the dynamo at all, but when it is running on open circuit only. Under these conditions the value of e will be

$$e = n Z N_o - (r_a + r_m) C_s;$$

or, since here q has the value q_o,

$$e = n Z q_o S_s C_s.$$

But $e = C_s r_s$, whence we get

$$n = \frac{r_s}{S_s} \cdot \frac{1}{Z q_o}.$$

Comparing this value of n with that obtained in the first equation of condition, we get

$$\frac{r_s}{S_s q_o} = \frac{r_a + r_m}{S_m q};$$

whence, finally, as the *second* equation of condition,

$$\frac{S_s}{S_m} = \frac{r_s}{r_a + r_m} \cdot \frac{q}{q_o}.$$

As q_o is proportional to μ_o the initial permeability when the shunt only is at work, and q proportional to the average permeability μ for the range of working between zero current and maximum current, it follows that if there were no alteration of saturation, $q_1 \div q_o$ would equal 1. In the former editions of this work, wherein the theory of compounding was expressly based upon the supposition

that there was no saturation—or in other words, that the permeability was constant—the formulæ obtained were admittedly incorrect for this reason. Dr. Frölich found for a certain Siemens compound dynamo,

$$\frac{S_s}{S_m} = 17 \cdot 7, \text{ whereas } \frac{r_s + r_a}{r_a + r_m} = 61 \cdot 9.$$

From which it is clear that μ_0 must have been about $3 \cdot 5$ times as great as μ_1; in other words, this machine had an insufficient quantity of iron in its magnets or armature core, or in both. This dynamo must have been both badly designed and of low efficiency; r_s ought to have been not $61 \cdot 9$, but at least 300 times as great as $r_a + r_m$.

To compensate for the demagnetizing action of the armature, additional turns are required in the series coil, as explained above on p. 231. To make the last set of formulæ complete S should be replaced by $S - D v$.

Over-compounding.—It will be noticed that, apart from the demagnetizing action of the armature, the amount of excitation to be provided for by the series coils is always proportional to the resistances that are in the main circuit and *internal to the points for which the constant difference of potential is desired;* this renders it possible, in a case where the mains leading from the dynamo to the lamps are long, so to compound the dynamo by adding more coils in series as to give a constant potential, not at its terminals, but at the distant point of the circuit where the lamps are to be used. This is a most valuable circumstance in all cases where the lamps are far from the dynamo, as in the lighting of mines from machinery at the surface; for then by *over-compounding,* one can obtain a constant pressure, not at the terminals of the dynamo, but on the mains at some point in the midst of the lamp-network. There is another advantage in over-compounding, namely, that when the full load comes upon a machine, the engine, however carefully governed, generally slows down a little, tending to produce a further drop in the voltage. As an example of over-compounding it may be mentioned that the 6-pole street-tramway generator, described on p. 433, required about 4000 ampere-turns per pole on

open circuit, but had a series-winding which allowed an additional 6000 ampere-turns per pole at full load.

Arrangements of Compound Winding.—Compound windings may be arranged in several different ways. If wound on the same core the shunt coils are sometimes wound outside the series coils: as frequently the series coils are outside the shunt. It is advisable to keep down the resistance of the series coils, as they will form part of the main circuit; whilst the additional resistance necessitated by winding the wire in coils of larger diameter is not altogether a disadvantage in a shunt coil. In the former editions of this work the recommendation was made to wind the series coils nearer the pole than the shunt coils. If the magnetic circuit through the ironwork be good, the position of the coils makes little difference.

Practical Process for Compounding.—It is clear from the foregoing paragraphs that the compound machine, when run on open circuit, with only the shunt-current flowing, must give the same potentials at its terminals as it is to give as a compound machine. Hence this leads to the following practical process for compounding. Let the armature of the machine be run at the proper speed dictated by mechanical considerations, and let a voltmeter be applied at the terminals. Two experiments are then necessary. First, by means of temporary coils, having a known number of turns wound on the field-magnets, and furnished with measured currents from some accumulators or another dynamo, ascertain the number of ampere-turns that will suffice to excite up the magnets to this point. From this S_s can be determined; for C_s is known beforehand, say 2 per cent. of the whole current at full load. Secondly, put into the main circuit some resistance to represent the maximum load of lamps, and while the machine is running at its proper speed, ascertain, using still the temporary coil and accumulators, how many ampere-turns of excitation are needed in total when the machine is doing full work. Subtract from this the value of $C_s S_s$ obtained in the first experiment, and the remainder gives the number of ampere-turns which the series coil must furnish; and as the

maximum current is known, S_m can at once be calculated. The same process suits for over-compounding, the excitation at full load being raised until the volts at terminals rise to the higher number of volts that will allow for the drop in the leads.

Design of Constant Potential Machines.—It is obviously of importance in such machines that the iron parts should be so designed that (1) the characteristic should be as nearly straight as possible in that portion of it corresponding to the working range of currents for which regulation is desired; (2) that it should not turn down. Consequently, it is of importance in such machines that there should be just so much iron in the magnetic circuit that the current due to the shunt should carry the initial magnetization over the knee of the curve of magnetization; and that the reactions due to the armature currents should be small. Also, of course, the resistance of the armature should be kept as small as possible.

Characteristic of Compound Dynamo.—In the original theory of constant potential machines devised by Marcel Deprez, the argument was based upon the absence of saturation, and the presence of an initial independent magnetization. The following was the argument of Deprez. If there is a permanent excitement of magnetism quite independent of that due to the main-circuit coils of the dynamo, the characteristic (Fig. 157) will not start from O, but from some point above it depending on the amount of independent magnetization and on the speed. Let the starting-point be P. O P is the electromotive-force between terminals when the main circuit is open, but there is no external current until the circuit is closed, and then the characteristic rises in the usual fashion from P to Q. Draw O J at the proper slope to represent the resistance of the armature and series coils together. Now consider a line O E drawn at such an angle that the tangent of its slope represents the total resistance of the circuit at any particular moment. Then E x is the total

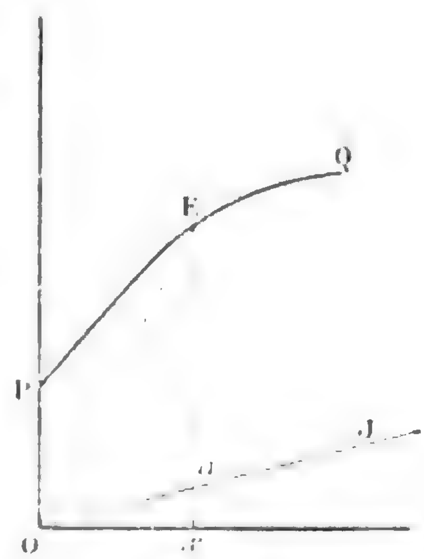


FIG. 157.

electromotive-force at that moment, and a part of this, equal to $a\,x$, will be employed in driving the current O x through the resistance of armature and series coils. The remaining part E a represents the difference of potentials between the terminals of the external circuit. So the problem resolves itself into this: how to arrange matters so that E a shall always be of the same length as O P, no matter how much or how little the line O E may slope. Clearly the only way to do this is so to arrange the speed of the dynamo that the part from P to Q shall be parallel to O J. If the speed is reduced exactly to the right amount the inclination of the characteristic will be equal to that of the line O J. Then, as shown in Fig. 158, the potential between the terminals will be constant. It will be seen that this agrees with the deductions arrived at in the algebraic treatment of the question: namely, that the critical speed is proportional to the internal resistance; and that the constant difference of potential E a is equal to that due to the independent magnetization O P at the critical speed.

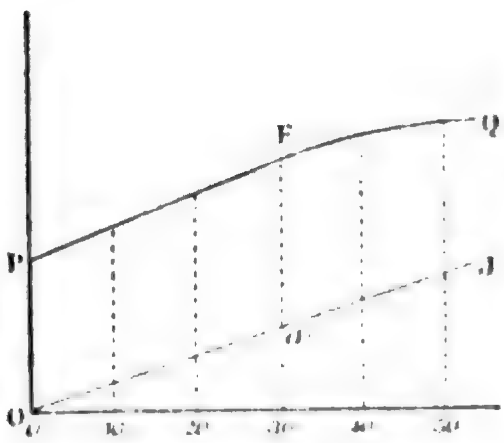


FIG. 158.

It should also be noticed that if the part of the characteristic be not straight, that is to say, if the field-magnet cores are becoming saturated, the regulation cannot be perfect. If the line P Q be curved, then the potential for large currents will not be equal to that for small currents. If, in the practical process for winding the magnets, the coils have been wound so as to make e the requisite number of volts, both on open circuit (i. e. at O P), and at another point (say at Q J), when the dynamo is feeding its maximum load, then there will in general be a slightly greater potential for intermediate loads, owing to the slight convexity of the curve between P and Q.

The above argument holds good whether the independent excitation be due to permanent magnetism or to a combination with separately-exciting coils (see pp. 55 and 231), or to shunt-exciting coils. In the latter case O P represents the potential at terminals due to shunt circuit alone.

The case of the "compound" dynamo is worth looking at from another point of view also. On p. 213 two curves—not characteristics—are given, showing the relation of electromotive-force to external resistance in a series machine and in a shunt machine.

One begins at a certain height and falls when the resistance has attained a certain value; the other begins low and rises when the resistance has attained a certain value. It is conceivable that if a dynamo were wound with both shunt and series coils, so that each worked up to the same potential and that they were so proportioned that the number of ohms at which one fell should be the same as that at which the other rose, then the compound machine should, as indicated in Fig. 159, give as a result of the double-winding, a constant potential.

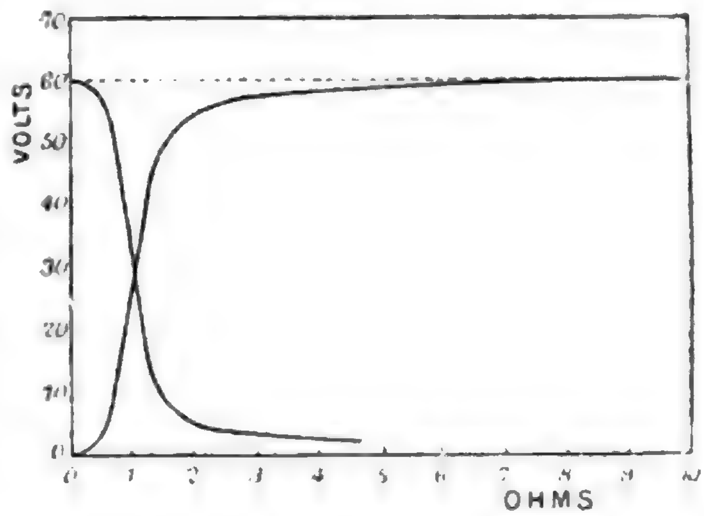


FIG. 159.

External Characteristics of Self-regulating Dynamos.—Simultaneous observations of the external current C and the external potential e enable us to plot the external characteristic; which in a perfectly self-regulating dynamo would be a horizontal line. If the number of regulating coils in series is too small, the characteristic will fall as the current rises; if too large, will droop slightly at the end near the origin. This latter case, however, is not always a disadvantage, for with machines worked singly on an engine the speed often rises in consequence of imperfect governing when the load on the dynamo is small.

Esson's Observations.—Mr. W. B. Esson has examined why it is that compound dynamos wound so as to be self-regulating for a given speed, regulate fairly well at any speed within considerably wide limits. The explanation he gives depends upon the saturation effect in the iron. If the magnetism were strictly proportional to the ampere-turns of excitation, there would be literally a critical speed. The approximate rule $\frac{S_m}{S_s} = \frac{r_a + r_m}{r_s}$ gives the number of series coils much too low, for when the shunt coil has already excited a certain degree of magnetization, the series coil cannot produce a proportionate increase owing to the lesser permeability. In a series machine (designed to give a current of 20 amperes), the electromotive-force added to the machine by increasing the exciting current from 5 to 10 amperes is much greater than the electromotive-force added by increasing the current from 10 to 15 amperes. Again, a

100-volt machine (self-regulating), in which therefore the shunt gave excitement enough for 100 volts on open circuit, had series coils upon it which were able, when the shunt was removed and the full current on, to give 60 volts between terminals. The value of the series coils to excite magnetism is diminished as the excitation due to the shunt is increased. All this is, of course, due to the diminution in permeability of the iron of the machine as the degree of saturation increases. From this it follows that a certain relation must subsist between the speed of the machine and the degree to which the magnets are excited by the shunt coil. But the magnetism furnished by the shunt coil also depends on the speed, and increases with it. If, therefore, at one speed this relation is such as to produce self regulation, the relation will be almost equally true at other speeds.

Engineers desiring further information on compound winding of dynamos, are referred to a series of articles in the *Electrician*, in 1883, by Mr. Gisbert Kapp; also to two articles by Mr. Esson in the *Electrician* of June 1885. Articles by M. Hospitalier in *L'Électricien*, and by Herr Uppenborn in the *Centralblatt für Elektrotechnik*, should also be consulted; and the student should above all read the series of papers published by Dr. Frölich in the *Elektrotechnische Zeitschrift* for 1885, and a still more remarkable paper by Professor Rücker in the *Philosophical Magazine* of June 1885. Some account of these was given in the Appendices of the third edition of this book. The latest contributions to this question are by C. Zickler, *Centralblatt für Elektrotechnik*, ix. 264, 1887, and M. Baumgardt, *ib*. x. 281, 1888; and by Dr. Louis Bell, in the *Electrical World*, xvi. 383, 1891.

CHAPTER XII.

ON WINDING OF ARMATURES (CONTINUOUS CURRENT).

THIS chapter is devoted to the theory of the ways of joining up and combining the conductors on the armatures of dynamos. Workshop details concerning materials and modes of construction are considered in Chapter XIII.

It has been pointed out, on p. 39, that continuous-current dynamos are usually provided with closed-coil armatures, that is to say armatures on which, whether wound according to the ring, drum, or disk type, the winding is re-entrant on itself, the current dividing between at least two paths and reuniting as it leaves the armature. For machines with two poles there are but two such paths, the current dividing once only. But for multipolar machines there may be either two, or more than two, such paths; with one, or more than one, bifurcation of the current. The electromotive-force of the machine will obviously depend on the mode of connexion of the conductors as to how many active conductors are connected in series. Hence the necessity of understanding the theory of armature winding.

To connect up rightly the conductors on an armature so as to produce the desired result is a simple matter in the case of ring-winding, for continuous-current machines, whether of bipolar or multipolar type. It is a much less easy matter in the case of drum-windings, especially for multipolar machines. Often there are several alternative ways of arriving at the same result; and the fact that methods which are electrically equivalent may be geometrically and mechanically different makes it desirable to have a systematic method of treating the subject.

In Chapter III., pp. 36 to 44, we have already considered

the elementary structure of ring, drum and disk armatures. Those elements would suffice for the consideration of small armatures coiled with only a few turns of wire. But when we proceed to the design of large machines, or of machines which are to be wound so as to give potentials as high as 400 or more volts, further information is needed. For example, suppose we have designed a 4-pole machine having a bar-armature with 100 bars spaced around its periphery, all in one layer, numbered consecutively from 1 to 100, and we desire to complete the end-connexions; we must be able to instruct the workman as to the order in which they are to be connected. Is he to connect the front[1] end of bar No 1 right across to bar No. 50, or No. 49? Or is he to connect it across a quarter of the periphery, and, if so, is it to join No. 25 or No. 24, or to No. 75 or No. 76? To which return-bar is he to connect the back end of the bar? And which bars are to be connected down to the commutator?

The object of the present chapter is to give information on these points. Brevity is essential; and much more might have been written. Those who wish to go further should consult the writings of Hering,[2] Arnoux,[3] Fritsche,[4] Weymouth,[5] Arnold,[6] Parshall and Hobart,[7] as well as sundry specifications to which reference will be made.

As remarked above, there is generally little trouble in understanding a ring winding, provided the distinction between a right-handed and a left-handed winding is comprehended.

Fig. 160 shows one section of a ring, the direction of the currents being indicated in the same way as on p. 72, Figs. 60 to 62. As we pass right-handedly around the circle from *a* to *b* we follow a right-handed spiral path, the current climbing

[1] "Front" end means the end where the commutator is; armatures being always most conveniently regarded from this end.

[2] Hering: *Principles of Dynamo-Electric Machines*, New York, 1891.

[3] Arnoux: *L'Électricien*, xii. 737, 774, 827, 1888.

[4] Fritsche: *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

[5] Weymouth: *Drum Armatures and Commutators*, London, 1893.

[6] Arnold: *Die Ankerwickelung der Dynamomaschinen*, Berlin, 1891.

[7] Parshall and Hobart: *Armature Windings of Electric Machines*, New York, 1895.

(as explained on p. 60) to the positive brush at the top. (A left-handed coiling, such as Fig. 31, p. 38, would give the positive brush at the bottom, unless either the rotation or the polarity of the dynamo were reversed.) To say whether a drum armature is right-handedly or left-handedly wound we must first settle upon the particular end of it from the point of view of which our statement is to be applicable; for instance the commutator end is conveniently taken as the one at which we are supposed to be looking. And we must also fix upon a certain sense of rotation (say clockwise) in which we intend to take the order of the commutator bars. These two matters being fixed arbitrarily, then a right-handed winding may be

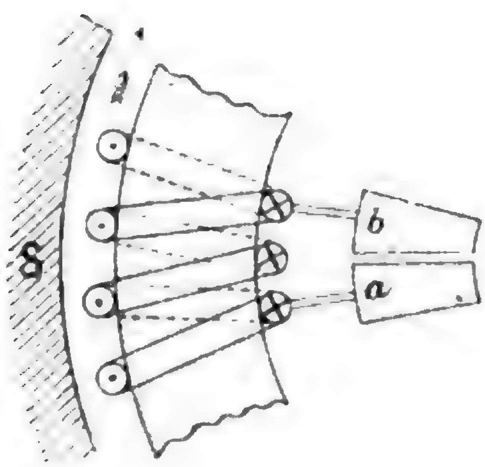


FIG. 160.—RIGHT-HANDED RING-WINDING.

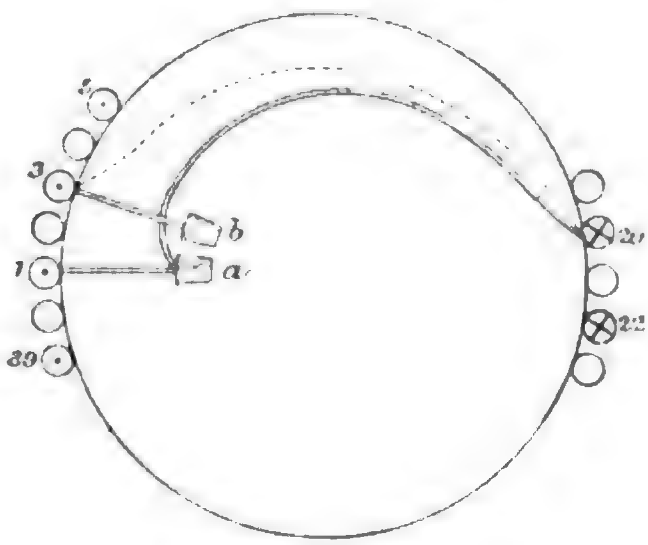


FIG. 161.—RIGHT-HANDED DRUM-WINDING.

defined as follows. That winding is right-handed which in leading from one bar to the next (in the order fixed as above) forms a right-handed screw. Now consider Fig. 161, which depicts one element or section of a drum-winding having 40 external conductors. Starting from *a* to climb to *b*, and noting the direction of the currents in the conductors, it is obvious that *a* must be connected by a spiral connector across the front end of the drum to one of the descending conductors such as No. 20, from which at the back end another connector must join it to one of the ascending conductors, such as No. 3, where it is led to *b*, thus making one right-handed turn. Now examine Fig. 173, p. 259, and Fig. 178, p. 263. They are both

left-handed, the latter having eight turns of wire in one section. Note in passing that if the back connector in Fig. 161 from No. 20 to No. 3 had passed under the shaft, instead of over it, the winding would still have been a right-handed winding.

The next point is to ascertain over how many conductors these spiral connectors ought to pass. We connected No. 1 (*viâ* the bar *a*) to No. 20, and then back to No. 3. Is there any reason why No. 20 should have been chosen and not No. 21, or No. 19, or No. 18. To understand this we must consider the question of commutation in the conductors as a whole, and also remember that there are two paths through the windings from brush to brush. This is a drum with 40 conductors in one layer: and there will be 20 bars in the commutator. Remember that the induced electromotive-forces will be directed from back to front in the conductors rising on the left, and from front to back in those descending on the right. It is natural to think that each conductor ought to be joined to the one that lies diametrically opposite to it. In that case No. 1 should be joined to No. 21, No. 2 to No. 22, and so forth. But this will not do. Each conductor on one side needs a return conductor on the other side. The even numbers may be looked upon as the returns for the odd numbers. Hence No. 1 ought not to be joined to No. 21. Shall it be joined to No. 20 or to No. 22? or shall we join it to No. 18? Nos. 20 and 22 lie on either side of the one that is diametrically opposite, and electrically it makes no difference which we select of these two. If we are going to use a back connector which returns over the shaft (as in Fig. 161), there is a slight saving of copper if we select No. 20. If the back connector returns under the shaft, either may be taken. More copper will be saved if we select No. 18 and return over the shaft, as the spiral connectors will be shorter. But if we thus connect across a short chord of the circumference, instead of taking the chord nearest to the diameter, we risk getting counter electromotive-forces in the turns that are in series from brush to brush. On the other hand, as Swinburne has shown, connecting across a short chord has the advantage that the armature has a smaller demagnetizing action. The

effect of winding across a chord subtending the span of the pole-piece is shown by Fig. 162, in which it will be seen the belt of demagnetizing conductors between the pole tips is now replaced by a belt, in which the currents flow in two opposing directions, thus neutralizing one another. In no case should the chord subtend a less angle than that subtended by the polar face. The rule then for connecting is as follows for a simple 2-pole drum armature. The number of conductors Z being an even number, the front connector must cross from any conductor to that which is $\frac{1}{2} Z \pm 1$ further on (or $\frac{1}{2} Z \pm 3$ for shortening the chord); and the back connector must lead back to the next conductor but one. In the following winding-table the letters F and B stand for *front* and *back*, and the letters U and D stand for *up* and *down*, meaning toward the front end, and from the front end respectively. From this it will be seen that starting with conductor No. 1, we follow *down* it to the back, there connect it to No. 22, then come *up* to the *front*, then come (connecting to a bar of the commutator in passing) to No. 3, go down this, and connect across the

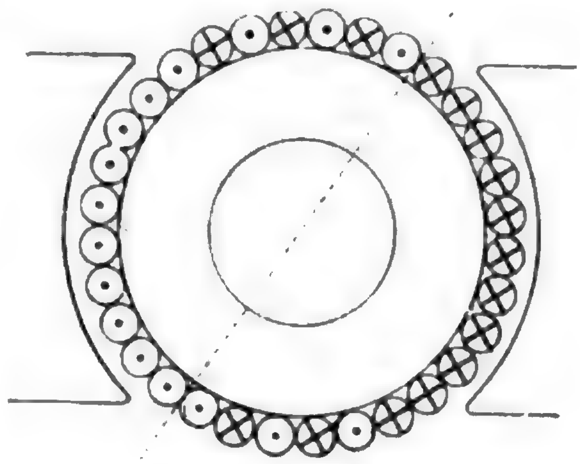


FIG. 162.—EFFECT OF CHORD-WINDING.

WINDING-TABLE. 2-POLE DRUM. 40 CONDUCTORS.

F	B	F	B	F	B	F	B	F
D	U	D	U	D	U	D	U	
1	22	3	24	5	26	7	28	
9	30	11	32	13	34	15	36	
17	38	19	40	21	2	23	4	
25	6	27	8	29	10	31	12	
33	14	35	16	37	18	39	20	

back to No. 24, and so on. The overlap is in this case + 21 at the back end, and − 19 at the front end. At last we come to No. 20, up which we return to the front and connect to No. 1 taking the last bar of the commutator on the way.

Simple as the matter may seem, the problem how to connect across the end of the drum from one conductor to that which is next but one, or next but three, to the diametrically opposite conductor, is not altogether easy when the mechanical and electrical difficulties are taken into account. To shorten the length of the long spiral connectors, and make the end-connexions more symmetrical, the arrangement indicated in Fig. 163 is now often used. The spirals are thus

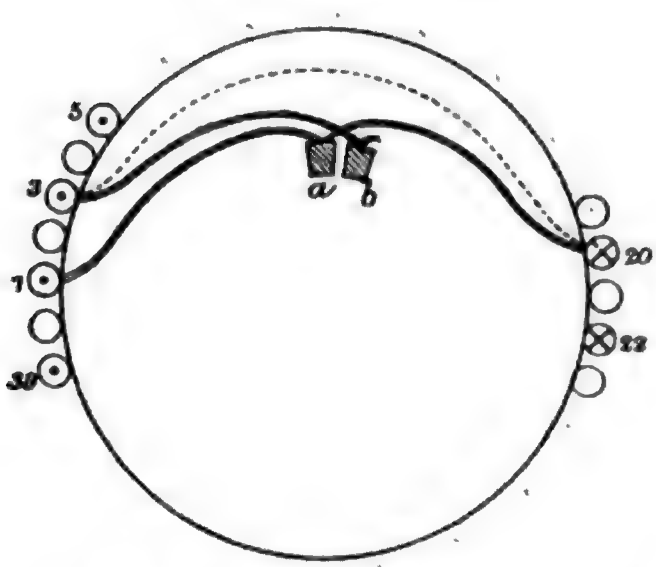


Fig. 163.—Drum-Winding with Two Sets of Spiral Connectors.

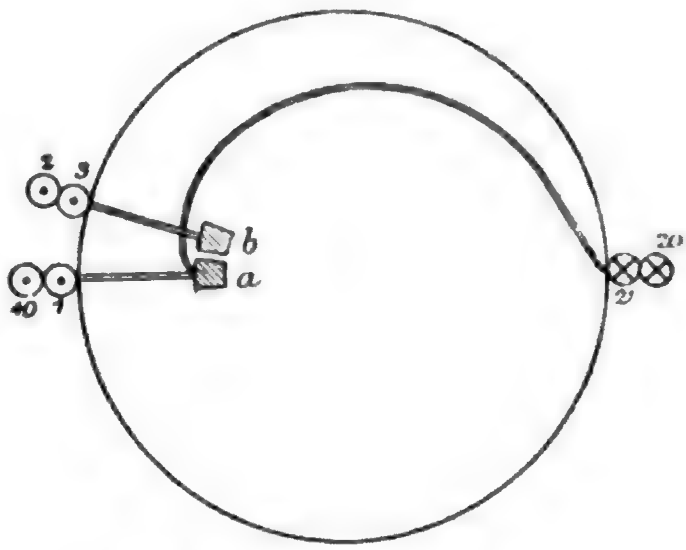


Fig. 164.—Two-layer Drum-Winding.

arranged in two layers one over the other, as in Figs. 231 and Plate IV., with the effect that the commutator has virtually been turned through about a quadrant, so that the + brush will be on the left instead of at the top. It has the advantage that all the spiral connectors at either end may be made of same size.

If, however, the conductors are arranged in two layers one over the other, the windings may be made across a diameter, the last turn being brought across to the next in the same layer. The conductors of the outer layer then answer instead of the intermediate members of the one-layer set. In Fig. 164 the end of No. 1 is brought to *a*

thence it spirals round to No. 21, which is connected across the back to No. 3, and so on. Fig. 165 shows how the 80

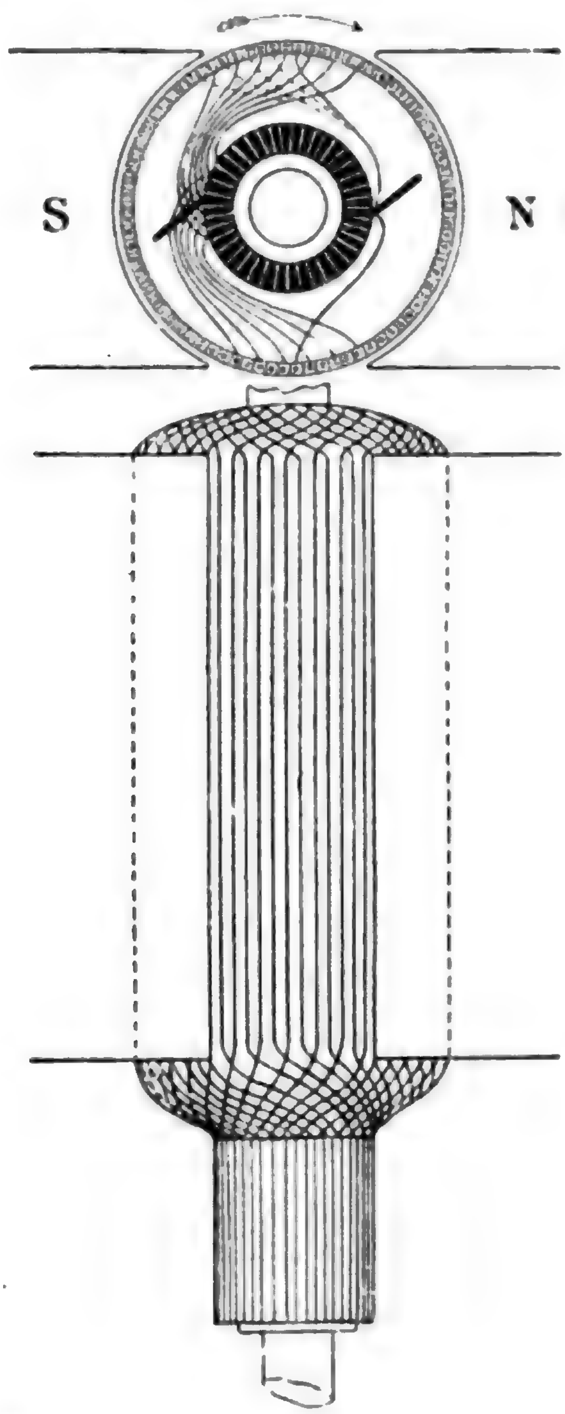


FIG. 165.—DRUM-WINDING OF EDISON-HOPKINSON DYNAMO.

conductors of the wire-wound Edison-Hopkinson armature (see p. 353) are connected, there being in reality two layers of 40 each, and a 40-part commutator.

DEVELOPED WINDING DIAGRAMS.

There is a great advantage in adopting a mode of representation (originally suggested by Fritsche of Berlin) in which

the armature winding is considered as though the entire structure had been developed out on a flat surface.

Consider first Fig. 166, which is a partial sketch of a four-pole machine laid on its side. The core, which may be hereafter wound either as ring or as drum, lies between the four poles of alternate polarity. If a copper rod *a* is placed parallel to the axis to represent one of the armature conductors, and is supposed to move along the gap-space right-handedly past the S pole, it will cut the magnetic lines entering that pole. By the rule given on p. 22, the induced electromotive-force in it will be upwards. Another conductor *c* passing the N pole will have induced it in a downward electromotive-force. If one were to attempt in a picture such as this to show twenty or more conductors and their respective connections, the drawing would be unintelligible. Accordingly we have to imagine ourselves placed at the centre, and the panorama of the four poles around us to be then laid out flat, as in Fig. 167. It will be noticed that the faces of the N and S poles are shaded obliquely for distinction [1]

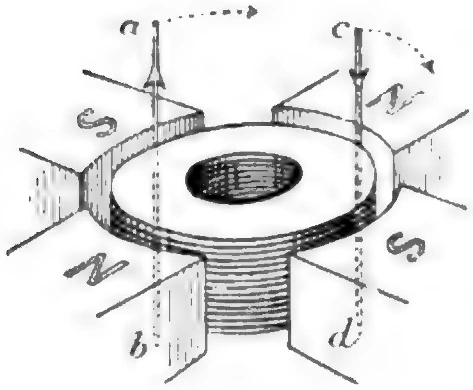


FIG. 166.—SKETCH OF 4-POLE FIELD.

Now in an actual machine there are many armature conductors spaced symmetrically around, and these have to be grouped together by connecting wires. In the case of ring windings the wires which connect the active conductors in the gap-space pass through the central aperture in the ring when they are removed from the magnetic field. Suppose, for simplicity, we have a ring armature of only 12 turns, and 12 bars to the commutator. If this is opened out from the

[1] I choose these oblique lines for the following reason. If instead of the line *a b* (representing a conductor), a narrow slit in a piece of paper were laid over the drawing of the pole-face, and moved as the dotted arrows show towards the right, the slit in passing over the oblique lines will cause an apparent motion in the direction in which the current tends in reality to flow. It is easy to remember which way the oblique lines must slope; for those on a N pole-face slope parallel to the oblique bar of the letter N.

inside we shall have the form shown in Fig. 168 where the dotted lines are the inactive parts of the spiral winding that pass through the inside of the ring. By tracing the arrows it

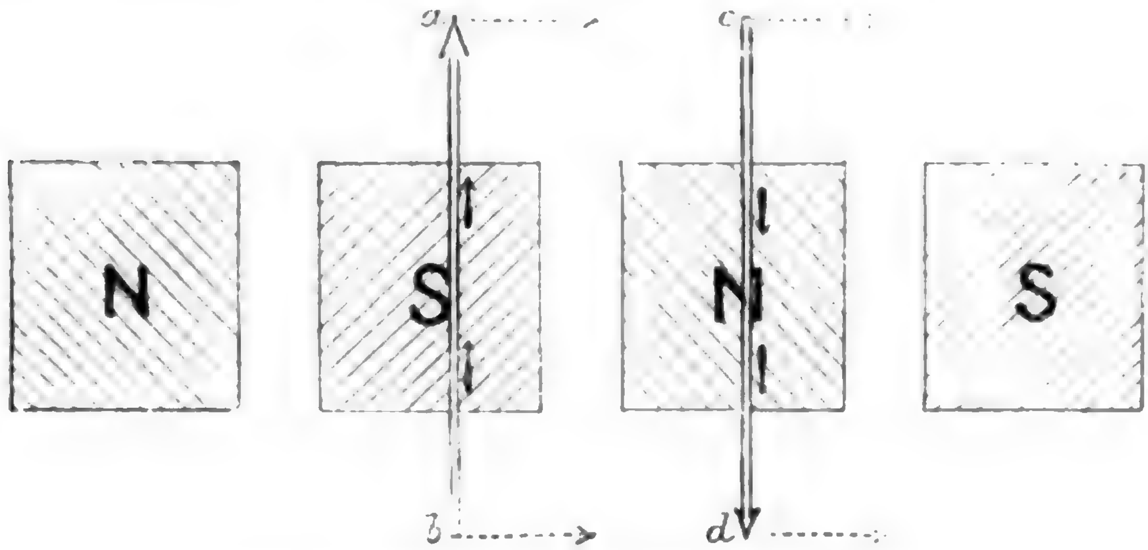


FIG. 167.—4-POLE FIELD DEVELOPED FLAT.

will be seen that there must be two positive and two negative brushes. Fig. 169 gives an end-view diagram of the same winding, by which the two modes of presentation may be

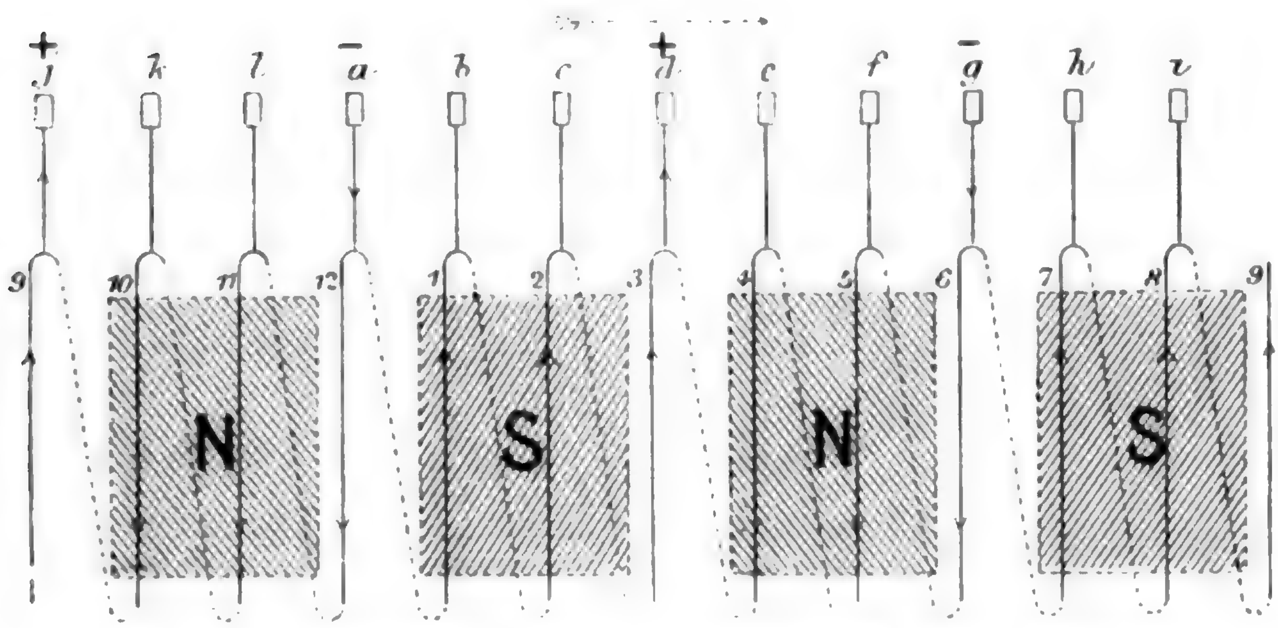


FIG. 168.—DEVELOPMENT OF RING-WINDING FOR 4-POLE MACHINE.

compared. It is clear that in this case the armature might be used as two separate machines to furnish two separate currents, though this would not be desirable. It is usual to

couple the positive brushes together, and the negative brushes together. A 6-pole machine would require six brushes, and so forth. The reader should examine the cuts of the Berlin dynamos, Plate VIII. When the brushes of the same sign are thus connected together the electromotive-force of the whole armature is simply that of any of the sets of coils from one + brush to the adjacent − brush. In this 4-pole machine the

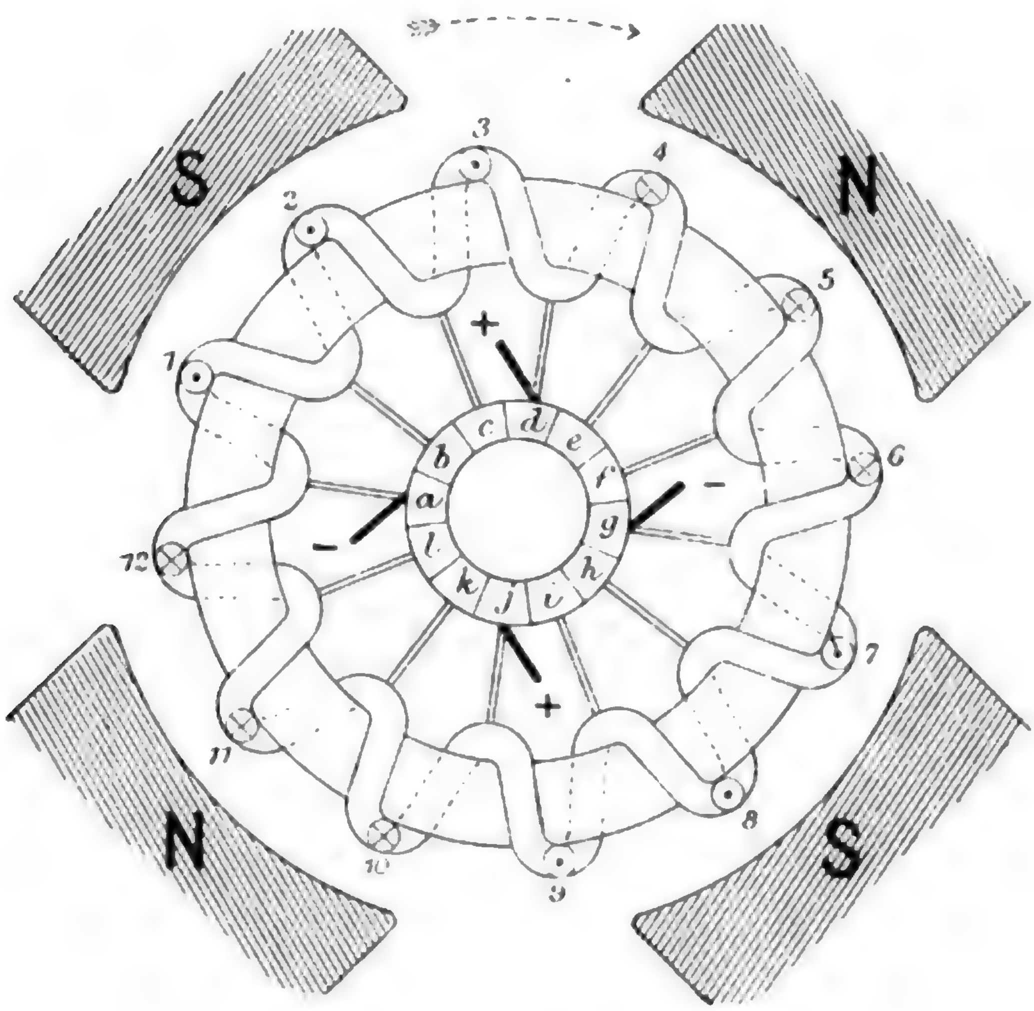


FIG. 169.—RING-WINDING FOR 4-POLE MACHINE (CORRESPONDING TO FIG. 168).

coils of the four quadrants are in four parallels; the internal resistance is one-sixteenth of the total resistance around the entire ring. There is, as we shall see, another mode of connecting the coils of a multipolar ring, in which the quadrants, instead of being all in parallel, are in series, so as to give two parallels only. This mode is sometimes called *multipolar series*, or *single circuit* winding; it would be more appropriately called *series-grouping*. It requires only two

sets of brushes at neutral points on the commutator, however many poles there are around the ring.

In further applying the method of development to those cases in which the winding is entirely exterior to the core, as

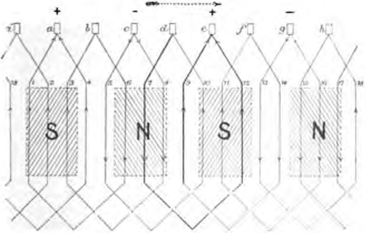


FIG. 170.—TYPICAL LAP-WINDING.

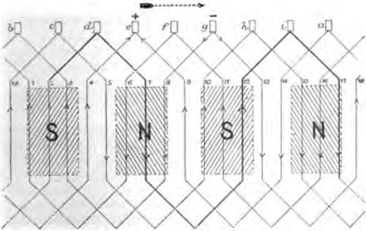


FIG. 171.—TYPICAL WAVE-WINDING.

for drum armatures, or to those in which there is no core at all, namely for disk armatures, we find that there are two distinct modes of procedure, which we may respectively denote[1] as *lap-winding* and *wave-winding*. The distinction arises in the following manner. Since the conductors that are passing a north pole generate electromotive-forces in one direction, and those that are passing a south pole generate electromotive-forces in the opposite direction, it is clear that a conductor in one of these groups ought to be connected to one in nearly a corresponding position in the other group, so that the current may flow down one and up the other in agreement with the directions of the electromotive-forces. If now we examine Fig. 170 we shall see that at the back of the armature (or end distant from the commutator) each conductor is united to one five places further on—No. 1 to No. 6, No. 3 to No. 8—and that at the front end the winding, after having made one "element" (as for example *d*-7-12-*e*), then forms a second element (*e*-9-14-*f*), which laps over the first; and so on all the way round until the winding returns on itself.

Now contrast with this Fig. 171, in which, though the connexions at the back end are the same, those at the commutator end are different. It will be seen that when the winding returns back toward the commutator, instead of lapping back toward the part from which it started, it is turned the other way. The winding *d*-7-12 does not return at once to *e*, but goes on to *i*, whence another element *i*-17-4-*c* goes on in a sort of zig-zag wave. These are both drum windings, the corresponding tables being as follows:—

It will be noted in passing that whilst with this particular number of conductors (18) the lap-winding results in four parallels of coils, and needs four brushes, the wave-winding results in two parallels, and requires two brushes only.

[1] The wave-winding is Fritsche's *Wellen-wickelung*; the lap-winding is called by Arnold (*op. cit.*) *Scheitel-wickelung*. Wave-windings were early used by Matthews, Bollmann, and Müller; and by Ferranti and Lord Kelvin for alternate-current generators.

WINDING-TABLE FOR FIG. 170.
(LAP-WINDING).

F		B	F
+ *a*	1	6	*b*
b	3	8	*c*
− *c*	5	10	*d*
d	7	12	*e*
+ *e*	9	14	*f*
f	11	16	*g*
− *g*	13	18	*h*
h	15	2	*i*
i	17	4	*a*

WINDING-TABLE FOR FIG. 171
(WAVE-WINDING).

F		B	F
a	1	6	*f*
f	11	16	*b*
b	3	8	*g*
- *g*	13	18	*c*
c	5	10	*h*
h	15	2	*d*
d	7	12	*i*
i	17	4	*e*
+ *e*	9	14	*a*

WINDING FORMULÆ FOR CLOSED COIL ARMATURES.

General formulæ for connecting—applicable chiefly to drum-windings—have been given by Hopkinson, by Müller and by Arnold. We shall follow the latter in the main. There is no difficulty about ring-windings; but a few special cases are separately considered later. With drum-windings, however, certain complications arise needing discrimination.

In deducing a formula for finding the proper spacing of conductors in a drum armature, it is well to begin with a bipolar machine, and then afterwards consider the effect of having more than two poles. We have seen from Fig. 161 that it is desirable in order to obtain a symmetrical winding to set aside the even numbers as returns for the odd numbers. Now in Fig. 161 there is only one spiral round the armature in passing from the bar *a* to the bar *b*, but in a high-voltage machine there might be several spirals. However many there may be, we will call this portion of the winding that lies between two commutator bars an "element" of the winding. Suppose it consisted of five spirals, then there would be ten conductors in one element, that is to say, five conductors together in a group at one side of the

armature and a group of five almost opposite them. Each of these groups of five would form a "section" of the winding. We have to consider how many of these sections must be passed by in connecting-up conductors. The number so bridged over may be called the *spacing* and may be denoted by y (for example, if No. 8 section is connected to No. 15 then $y = 7$). It must always bear such a relation to total number of sections s, that as we go on step by step from one section to another, we do not arrive at the point from which we started until all the sections in the armature have been included. If we denote the total number of conductors around the armature by Z and number of conductors in one "element" of winding by b, then $\frac{Z}{b}$ gives us half the number of "sections"; if we now add or subtract 1 from this number, we shall get a suitable number for the spacing in a bipolar machine. We have seen that we may add or subtract more than 1, as for instance, in a chord-winding, or in the case of a multiplex winding, as to which see p. 272. Denoting the number so added or subtracted by the letter a, we have as a suitable "spacing" for a bipolar drum-winding $\frac{Z}{b} \mp a$. Now, if the dynamo has got p pairs of poles the part of the winding extending under one pair of poles may be exactly the same as if those were the only poles existing, with this exception, that connectors may go from conductors in it to conductors in a second part of the winding, under an adjacent pair of poles, instead of going to similar conductors in it. If therefore we divide the expression given above by p, we will get the expression given by Arnold for the spacing in a multipolar drum, namely

$$y = \frac{1}{p}\left(\frac{Z}{b} \mp a\right);$$

$$Z = b\,(p\,y \pm a).$$

When we are dealing with multipolar drums the symbol a has a special significance. Putting chord-windings and multi-

plex windings out of account, for the sake of simplicity, a will be the number of bifurcations of the current through sets of coils that are in parallel with one another.

The number of neutral points on the commutator will be always $= 2\,a$. The number y must always be, relatively to s, a prime number, otherwise the winding will not be re-entrant as a closed coil. If they have a common factor (as, for example, $s = 36$, $y = 27$, where the common factor is 3) there will be as many *independent* circuits. In applying the formulæ we have several cases to deal with.

(*i.*) *Parallel Grouping.* We have seen in the case of an ordinary ring that there will, in a 4-pole field, be four rows of $\frac{1}{4}$ Z coils each in parallel with one another. Any grouping which results in as many rows in parallel as there are poles around the armature is called a *parallel grouping.* In a 12-pole field we should have 12 rows of $\frac{1}{12}$ Z each, in parallel. Each pair of such rows may be considered as constituting a separate 2-pole armature. It is also so for drum armatures if wound with lap-windings, but not if with wave-windings. The two cases stand thus for getting a parallel grouping :—

(*a*) *With Lap-winding* write in the formula $p = 1$ and $a = 1$, and apply it to a set of conductors lying between two poles of similar name.

(*b*) *With Wave-winding* write $a = p$; that is to say, there must be as many bifurcations of the current as there are pairs of poles. In a 6-pole machine $p = 3$, and the current will bifurcate at three points (the three negative brushes), going through six parallel paths to the three positive brushes (or to the cross connexions that lead to the positive brush).

(*ii.*) *Series Grouping.* For this, seeing that the current only bifurcates once, $a = 1$, whatever the mode of coiling. In the case of 2-pole machines the series grouping and parallel grouping are the same thing—there are two rows of coils in parallel with one another, and the winding may be either a wave-winding or a lap-winding. For 4-pole machines

the same holds good. For machines having more poles than four, however, the only possible cases of series grouping are wave-windings.

(*iii.*) *Mixed Groupings.* There are several possible cases of mixed lap- and wave-windings, corresponding to cases where $a > 1$ or $a \gtrless p$.

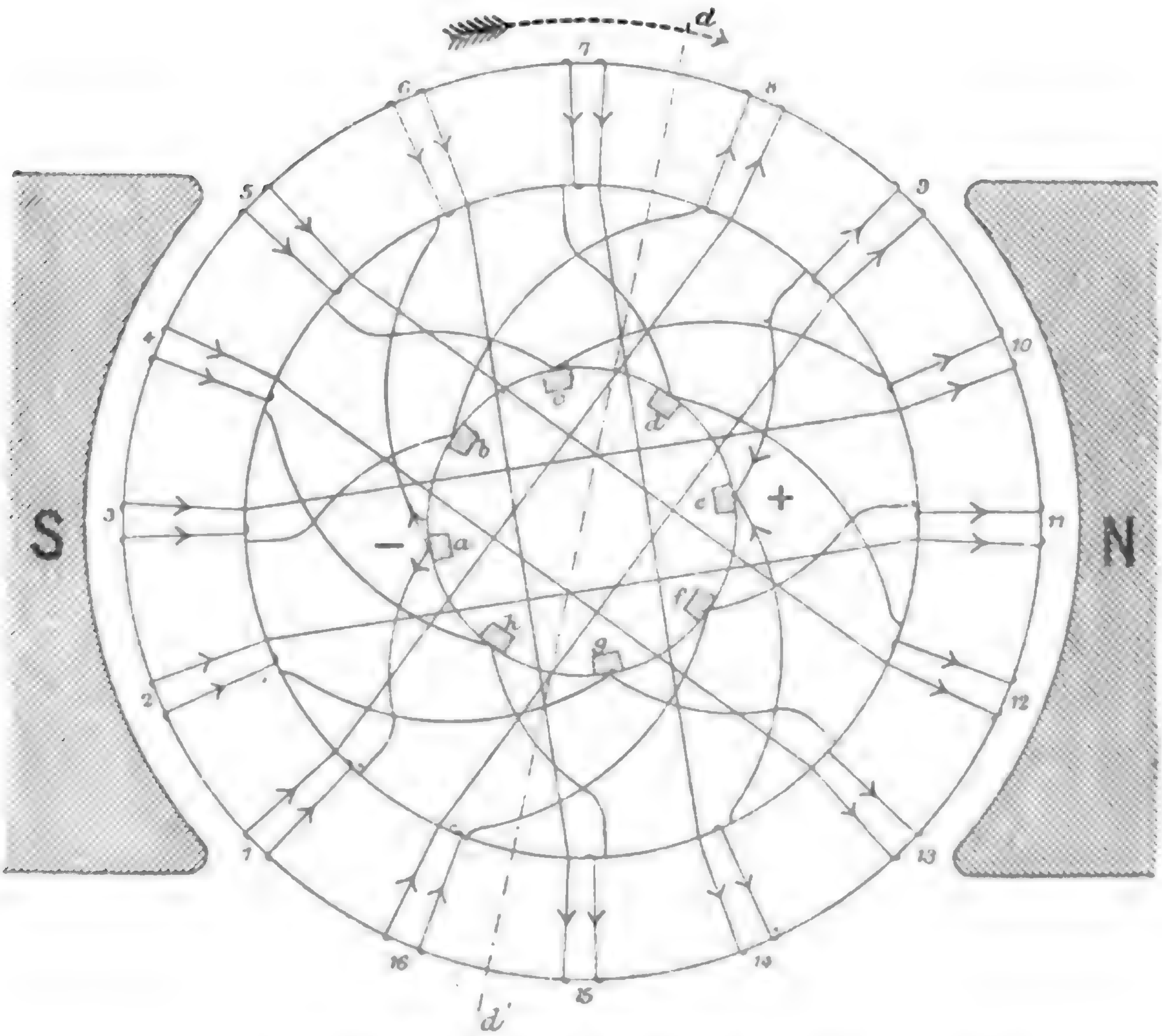


FIG. 172.—RING-WINDING WITH OPPOSITE COILS IN SERIES.

As examples for verifying these formulæ we may take the following :—

In the ring-winding Fig. 34, p. 40, $Z = 32$; $p = 1$; $b = 4$; $s = 8$; $c = 8$. Hence $y = 7$ or 9. But the ring has eight sections only, of which, therefore, the seventh and the ninth, reckoned from any given section, are those that lie on either side of it.

In the drum-winding, Fig. 69, p. 85, $Z = 32$; $p = 1$; $b = 2$ (because each "element" of the winding from bar to bar of the commutator contains two active conductors); $s = 16$; $c = 16$. Hence $y = 15$ or 17. The former number may be taken as referring to the front layer of connexions (No. 1 to No. 16), the latter to the layer below them (No. 2 to No. 19).

A further example is afforded by a special ring-winding used by Wodicka, Fig. 172, in which each section is joined in series with one on the side opposite to it, so that the number of commutator bars is half that of the sections. Here each "element" of the winding consists of two sections each containing active conductors; hence $b = 4$; $Z = 32$; $s = 16$; $p = 1$; whence y may be either 9 or 7.

Drum-Windings.

In Fig. 173 is given a drawing of drum-winding applied to an 8-part armature. As in all Siemens' earlier drums the windings lay in two layers, each section being wound diametrically. Thus starting from the bar of the commutator

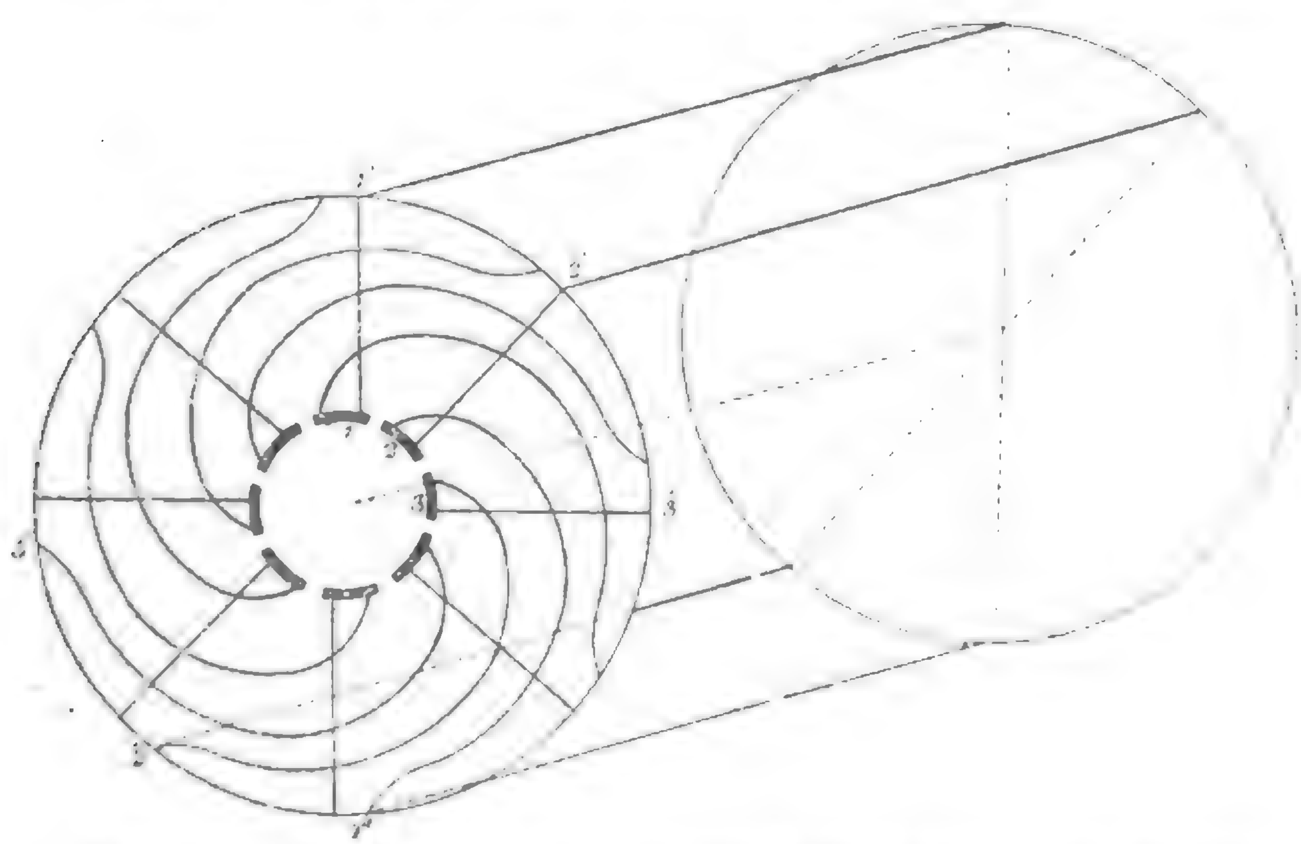


Fig. 173.—Connexions of Siemens (von Hefner-Alteneck) Winding.

marked 1 we pass outwards to 1′, then down the armature, across the back, up to 1″, and (after having wound a sufficient number of turns to form a section) spiral up to bar 2 of the commutator. The Edison variety of Siemens' winding is shown in Fig. 174. The diagram only shows a simple case with a 7-part commutator. Here S = 14; $b = 2$; and according to the formula y should be 6. But the actual value of the spacing is 7 at the back and 5 at the front end, as will be seen. With an odd number of sections commutation does not occur simultaneously (in bipolar machines) at both the brushes, but alternately.

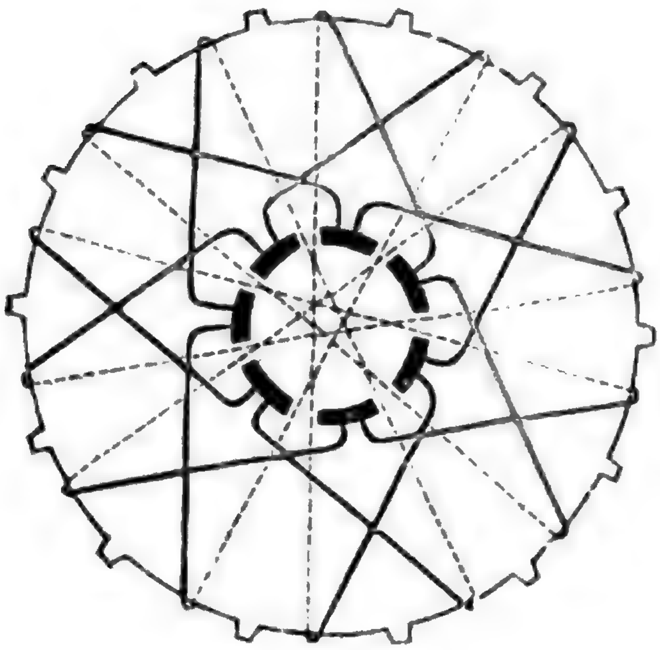
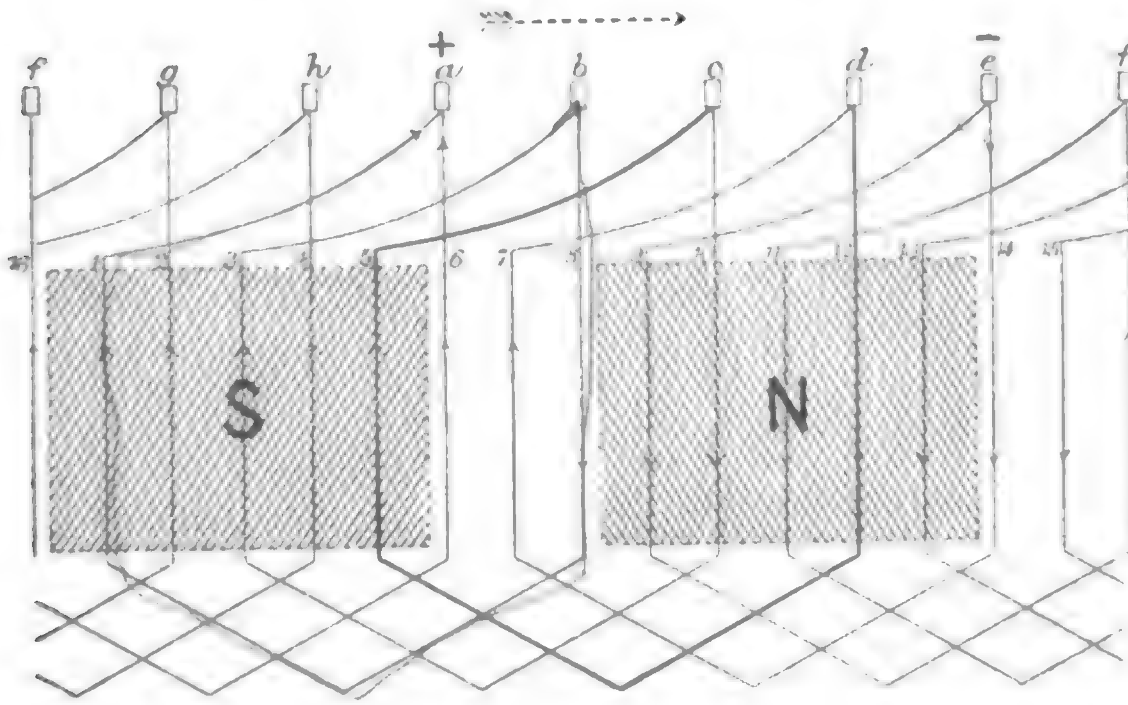


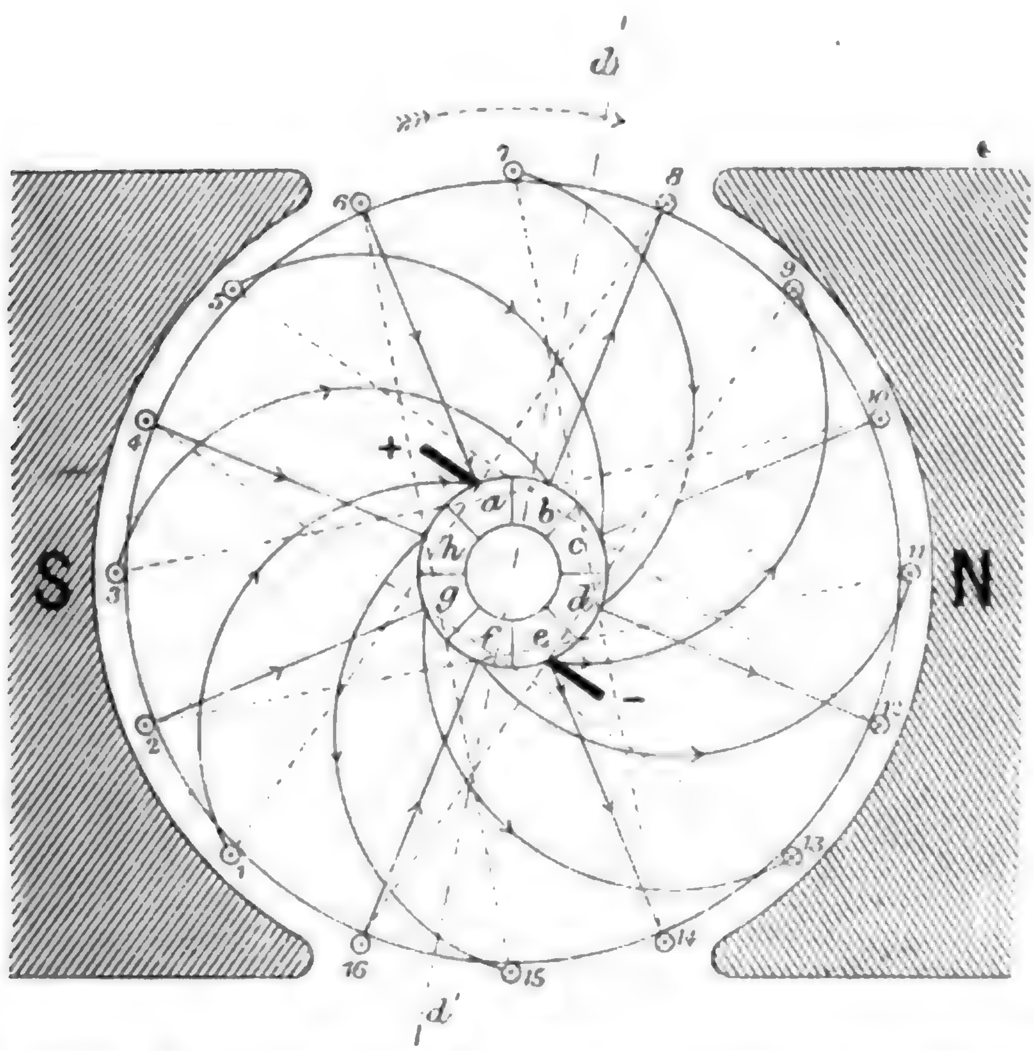
FIG. 174.—CONNEXIONS OF EDISON WINDING.

A closer study of the drum-winding is important, and accordingly there are given a series of winding diagrams relating to several varieties.

In Figs. 175 and 176 are given a right-handed winding on Siemens' plan for an 8-part commutator, and one turn to each section, *i.e.* with 16 conductors spaced round the periphery. The connecting pieces at the front end consist of straight connectors (such as *a* 6) and spiral connectors (such as *a* 1), which cross (either under or over) the former. The connecting pieces at the back end are not further indicated than by the dotted lines drawn across. In the developed diagram it is shown that each element of the winding is similar to *c*–5–12–*d* and that the arrangement is a lap-winding. The back connectors space over seven conductors, being just short by one of the number $\frac{1}{2}$ Z in the semi-circumference; whilst the front connectors space over five, being short by three of the semi-circumference. It will be further noted that with this right-

handed winding, rotating right-handedly in a right-handed field, the + brush is near the top of the commutator.





FIGS. 175 and 176.—LAP-WINDING (SIEMENS' RIGHT-HANDED) DEVELOPMENT AND END VIEW.

Figs. 177 and 178 represent the same thing, except that the winding is left-handed, with the result that the + brush is now near the bottom of the commutator.

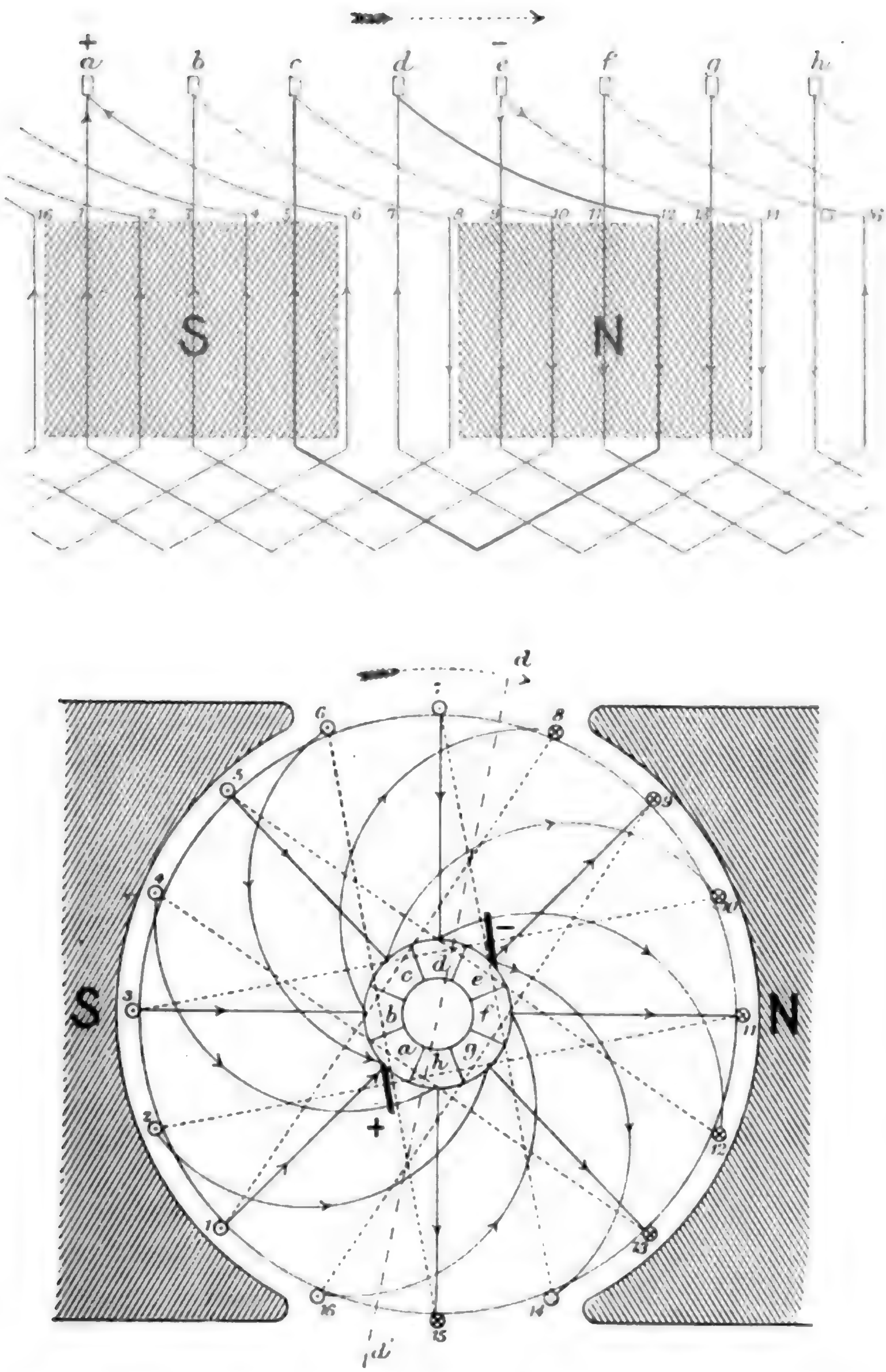
The winding table for both these figures is the same, namely :—

F	B		F
+ *a*	1	8	*b*
b	3	10	*c*
c	5	12	*d*
d	7	14	*e*
− *e*	9	16	*f*
f	11	2	*g*
g	13	4	*h*
h	15	6	*a*

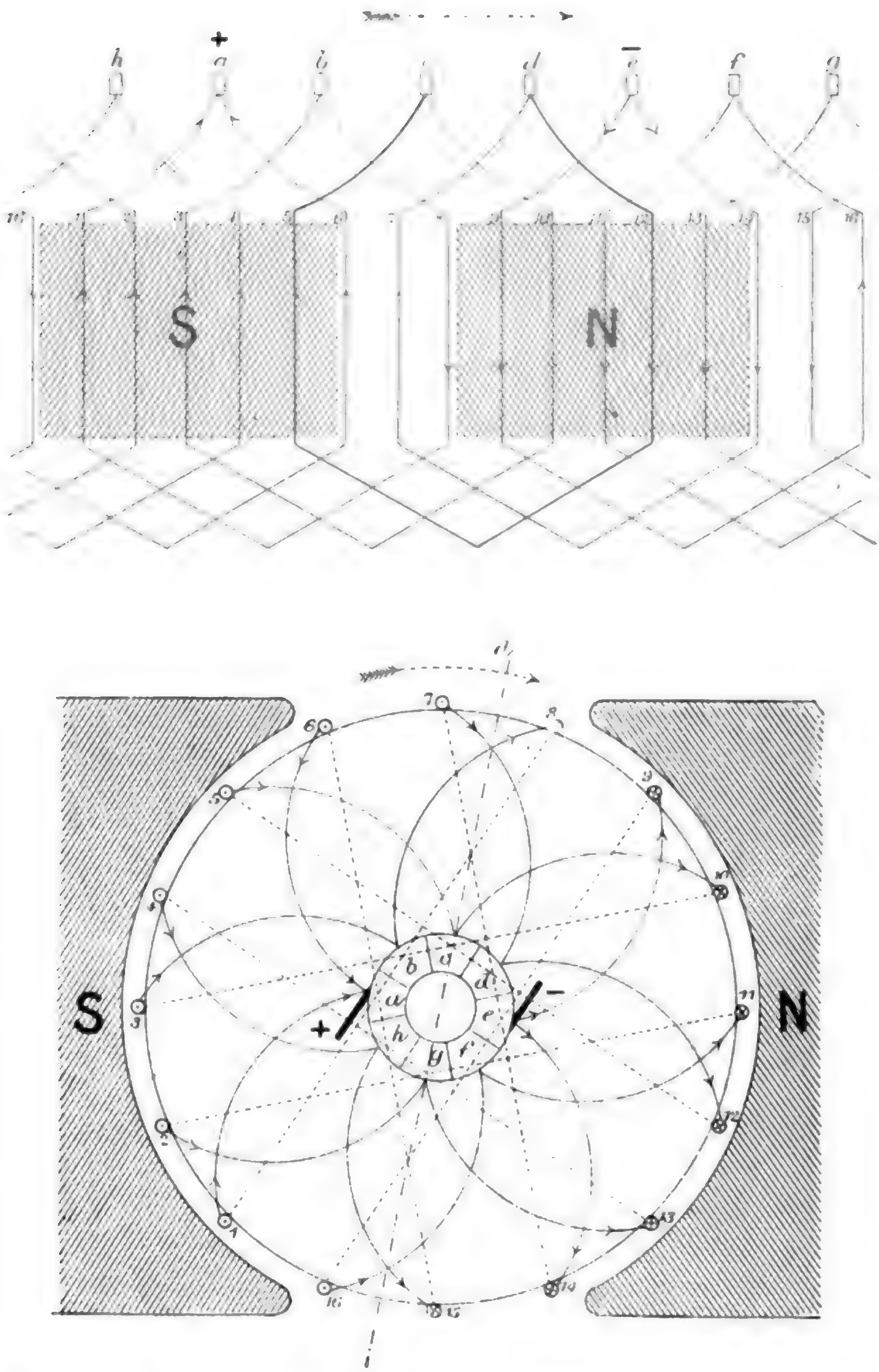
But in the right-handed winding the spiral connectors, such as *a* to 1, go toward the left, and in the left-handed winding to the right.

In Fig. 175 and Fig. 177 (the developments) it is seen that for both these windings the "element" of the winding, indicated by the darker lines, is unsymmetrical at the front front connectors, one straight, one spiral. The bar *a* of the end of the drum, this being due to the use of two sorts of commutator is connected to the front end of conductors No. 1 and No. 6. In one case it is skewed forward to be opposite No. 6; in the other it is skewed backward to be opposite No. 1. Why should it not be placed symmetrically between them?

Figs. 179 and 180 depict a symmetrical lap-winding, electrically precisely equivalent to the preceding, and having the same winding table. The advantages are twofold: that (for built-up armatures) the connectors at the front end are now all of the same pattern, consisting of two sets of short spirals; and that the brushes now come to a horizontal diameter where they are more accessible. The back connexions remain



FIGS. 177 and 178.—LAP-WINDING (SIEMENS' LEFT-HANDED) DEVELOPMENT AND END VIEW.



FIGS. 179 and 180.—LAP-WINDING (2-POLE SYMMETRICAL DEVELOPMENT AND END VIEW.

exactly as before, and go across a longer chord than the front connexions.

To secure the utmost symmetry in the winding, the back and front connectors ought to be equalised. The theoretically proper spacing is $y = 7$ or $y = 9$. To attain this, join No. 1 to No. 8 at one end of the drum and to No. 10 at the other. The result is shown in Figs. 181 and 182, from which it is at once apparent that we have passed from lap-windings to a wave-winding; each element passing around the drum and returning only to the next bar of the commutator from whence it started. The winding-table for this case is :—

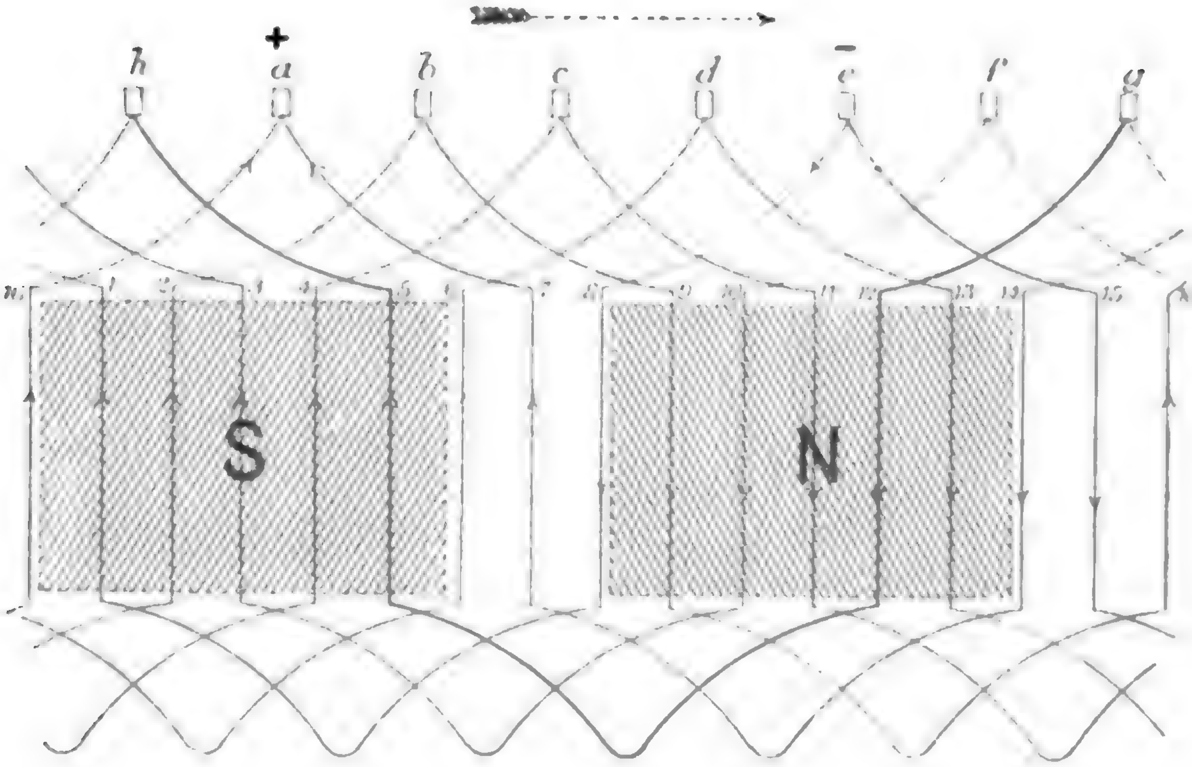
F		B	F
+ *a*	16	9	*b*
b	2	11	*c*
c	4	13	*d*
d	6	15	*e*
− *e*	8	1	*f*
f	10	3	*g*
g	12	5	*h*
h	14	7	*a*

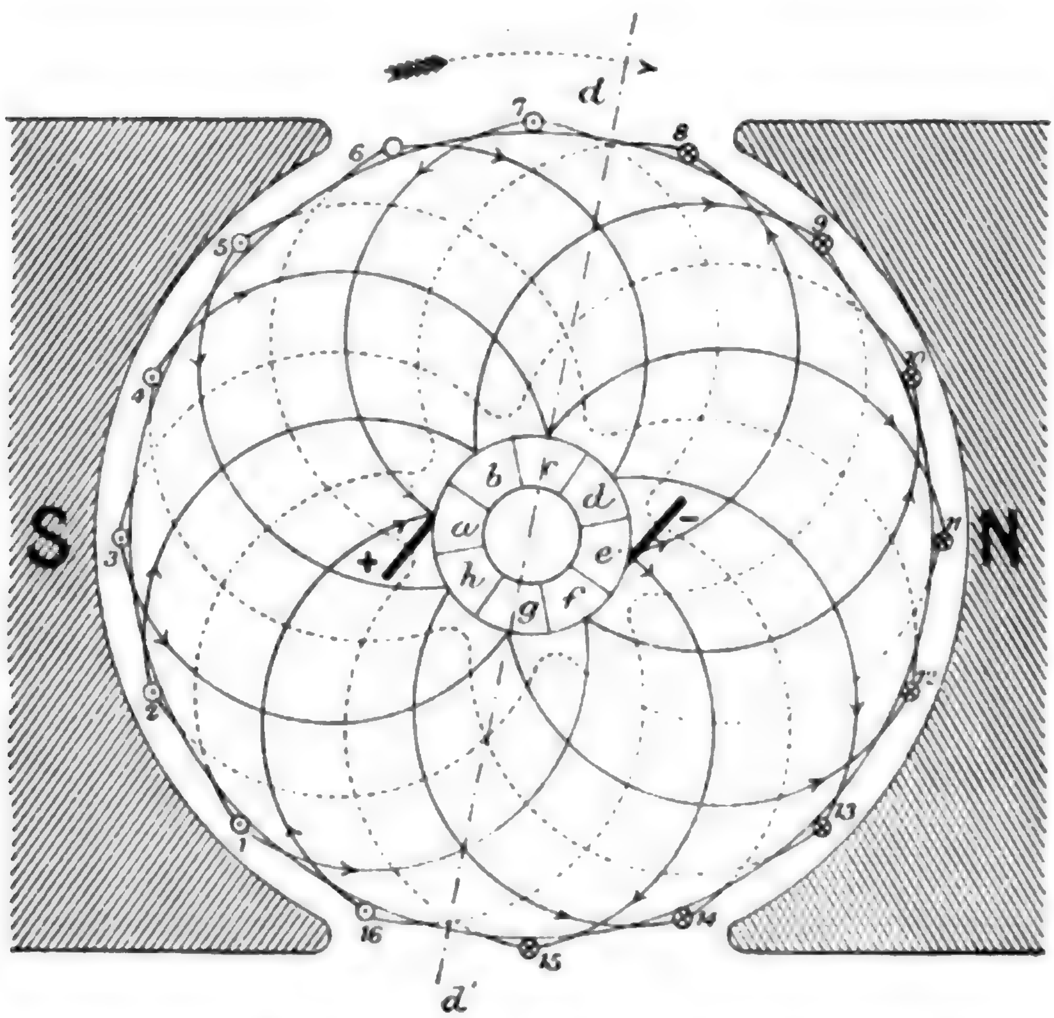
Electrically this winding is the precise equivalent of the three preceding. The spiral connectors at the back end meet in pairs as those at the front meet at the commutator.

A two-layer winding for twenty-four conductors, together with its development, are given in Figs. 183 and 184, showing how, when half the armature, from *a* to *g*, has been completed one layer has been wound.

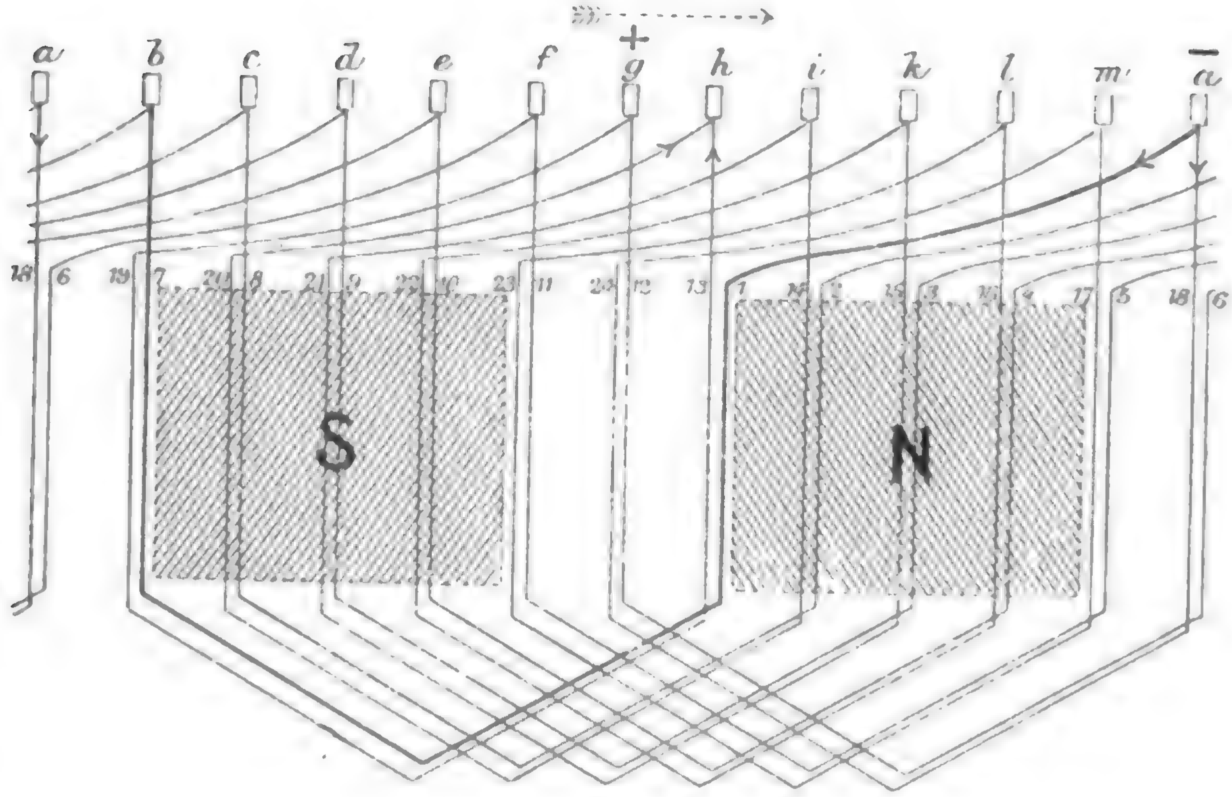
Multipolar Drums.—As mentioned on p. 278 below, the winding of multipolar armatures with series-grouping was suggested by Professor Perry.[1] It has been applied to drum-winding by Messrs. Paris and Scott,[2] and by Mr. Kapp. For the case of multipolar machines it is convenient to state the

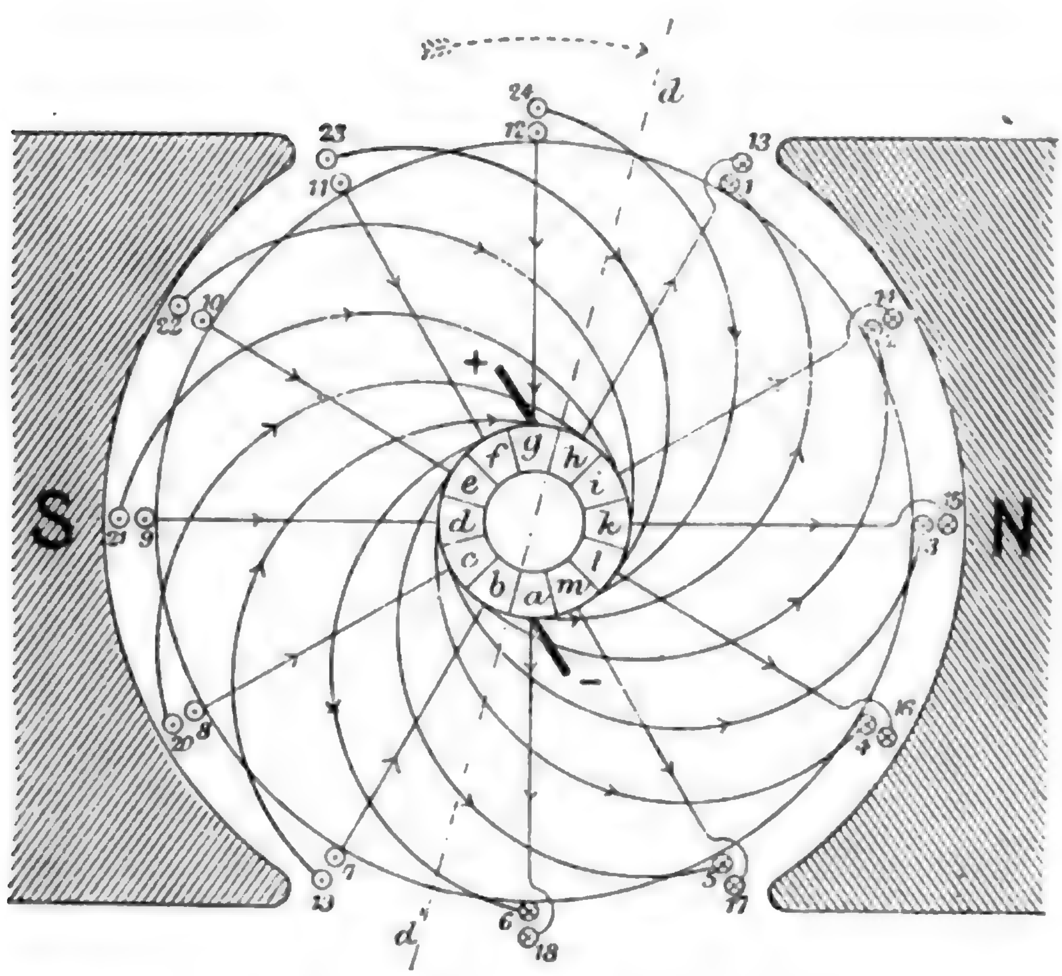
[1] Specification of Patent, No. 3036 of 1882.
[2] Specification of Patent, No. 4683 of 1884.





FIGS. 181 and 182.—WAVE-WINDING (2-POLE SYMMETRICAL) DEVELOPMENT AND END VIEW.





FIGS. 183 and 184.—TWO-LAYER DRUM-WINDING.

rule in words that if a series grouping (so as to give high voltage) is desired, y must be an odd number and that the total number of conductors must be equal to y times the whole number of poles, plus or minus two. For example; for a 6-pole drum, taking y as 15, the number of conductors must

WINDING TABLE FOR 8-POLE DRUM ARMATURE; 202 CONDUCTORS; SERIES GROUPING; BRUSHES (±) 135° APART.

F B F B F B F B F

D	U	D	U	D	U	D	U
202	25	50	75	100	125	50	175
200	23	48	73	98	123	148	173
198	21	46	71	96	121	146	171
196	19 −	44	69	94	119	144	169
194	17	42	67	92	117	142	167
192	15	40	65	90	115	140	165
190	13	38	63	88	113	138	163
180	11	36	61	85	111	136	161
186	9	34	59	84	109	134	159
184	7	32	57	82	107	132	157
182	5	30	55	80	105	130	155
180	3	28	53	78	103	128	153
178	1	26	51	76	101	126	151
176	201	24	49	74	99	124	149
174	199	22	47	72	97	122	147
172	197	20	45	70	95 +	120	145
170	195	18	43	68	93	118	143
168	193	16	41	66	91	116	141
166	191	14	39	64	89	114	139
164	189	12	37	62	87	112	137
162	187	10	35	60	85	110	135
160	185	8	33	58	83	108	133
158	183	6	31	56	81	106	131
156	181	4	29	54	79	104	129
154	179	2	27	52	77	102	127
152	177	202					

be either 88 or 92; not 90. On p. 268 is given a winding-table, calculated by Mr. Kapp for an 8-pole machine having a spacing of $y = 25$.

It may be remarked in passing that if in multipolar machines the number of sections is an exact multiple odd or even of p, the grouping will be parallel; and if it is an odd multiple then commutation will not occur simultaneously at all the brushes, but alternately at all the + brushes and at all the − brushes, similarly to the alternate commutation in a 2-pole machine when there is an odd number of sections in the winding.

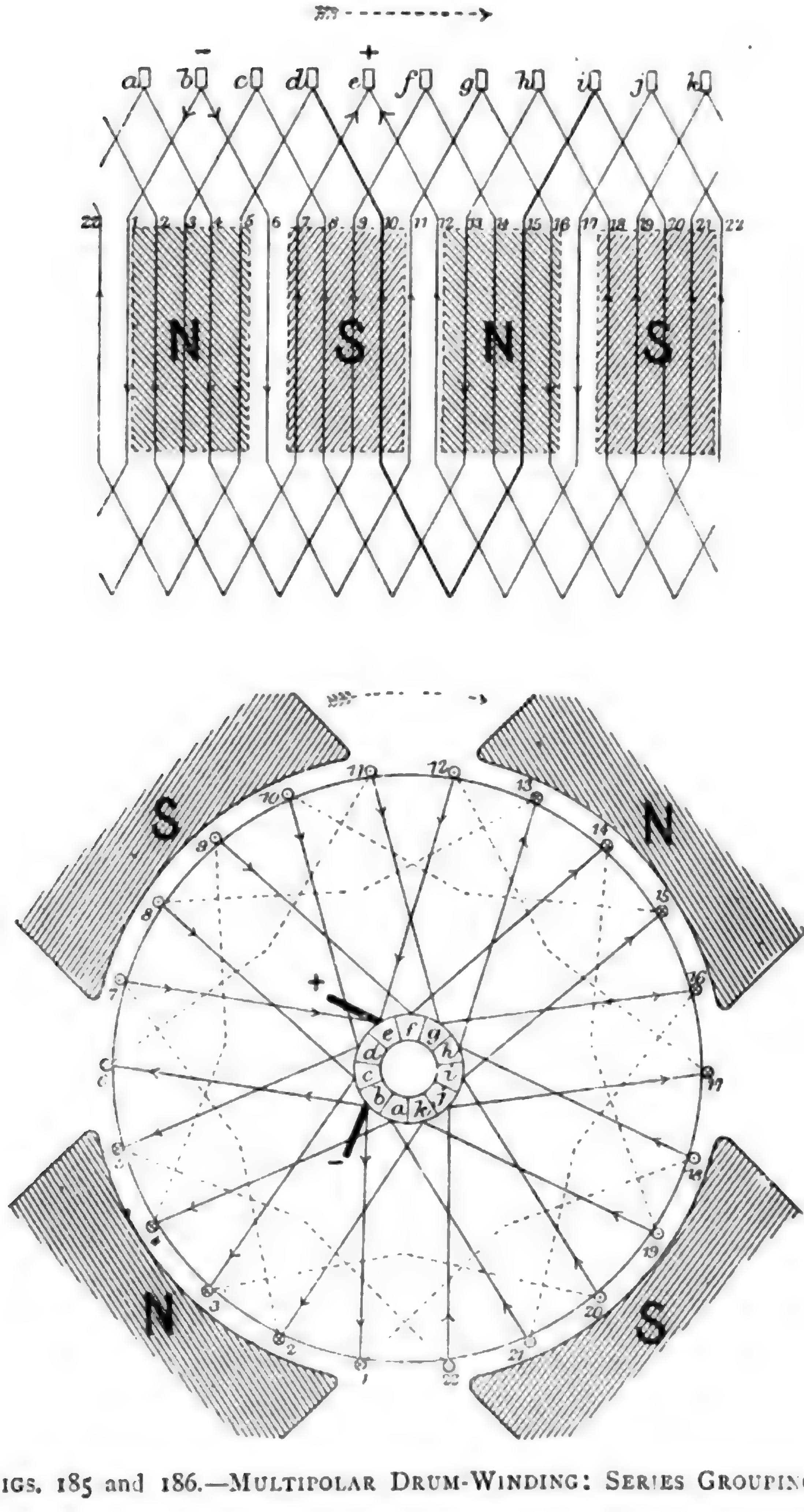
In Figs. 185 and 186 are given the connexions for a 4-pole drum-winding with twenty-two conductors; here $y = 5$. The winding-table for this armature is as follows:—

4-POLE DRUM: 22 CONDUCTORS: SERIES GROUPING.

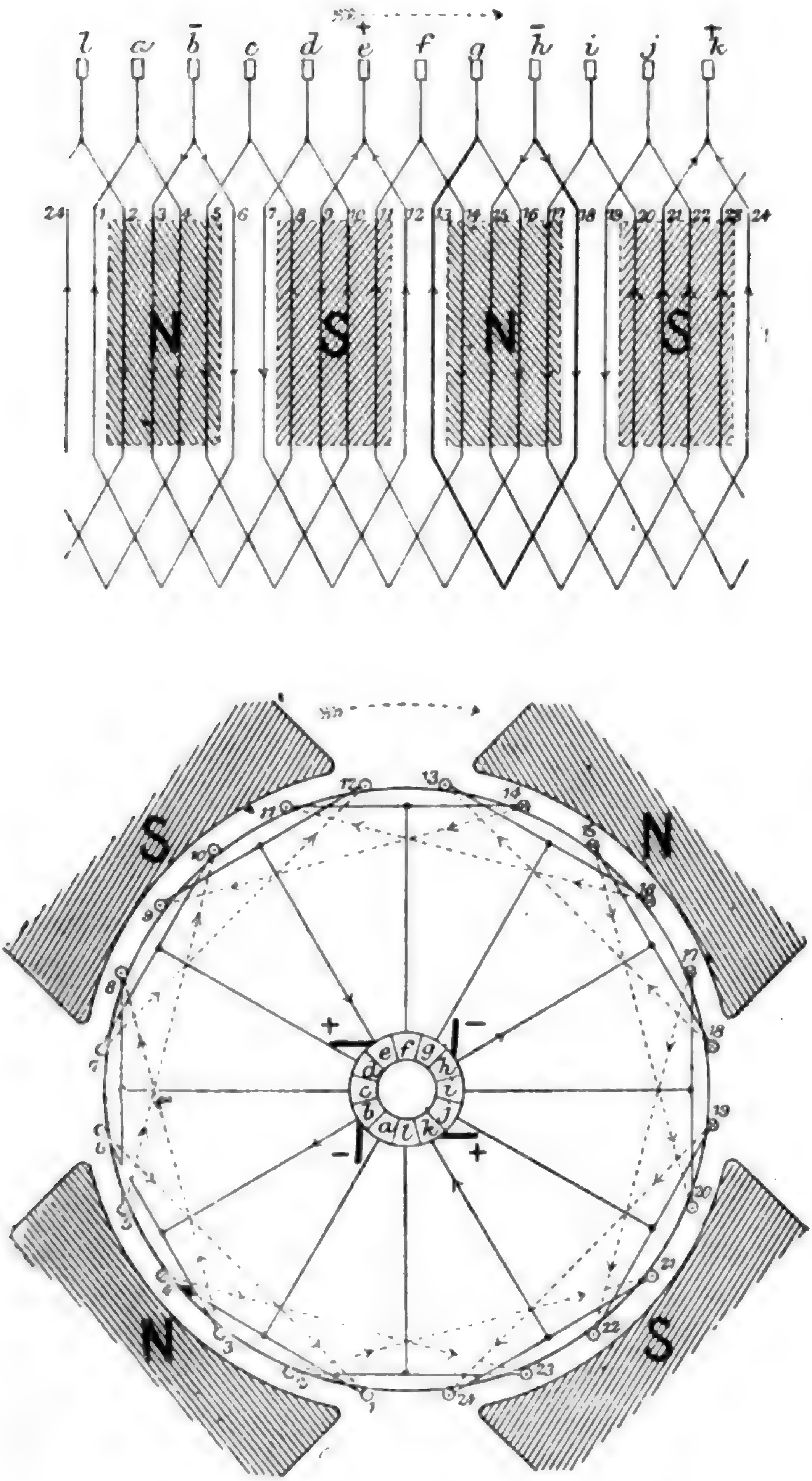
F	B	F	B	F

D	U	D	U
1	18	13	8
3	20	15	10
5	22	17	12 +
+ 7	2	19	14
9	4	21	16
11	6 −	1	

In Figs. 187 and 188 is given a lap-winding used by Thury (see Fig. 297, p. 442), the case illustrated being that of a 4-pole drum. It is a lap-winding for parallel grouping, with a spacing at the back end just short of the pitch of the poles and a still shorter spacing at the front end. This is a form of chord winding intended to keep conductors at very different potentials from overlapping, and it can be well insulated because the separate sections can be wound on formers before being laid over the core.



FIGS. 185 and 186.—MULTIPOLAR DRUM-WINDING: SERIES GROUPING.



FIGS. 187 and 188.—THURY'S ARMATURE (4-POLE LAP-WINDING.)

A method of drum-winding was proposed by Fritsche,[1] in which the conductors all lie obliquely across the surface of the drum, no part of them being parallel to the shaft. In this case the field-magnet poles are also constructed with diagonal

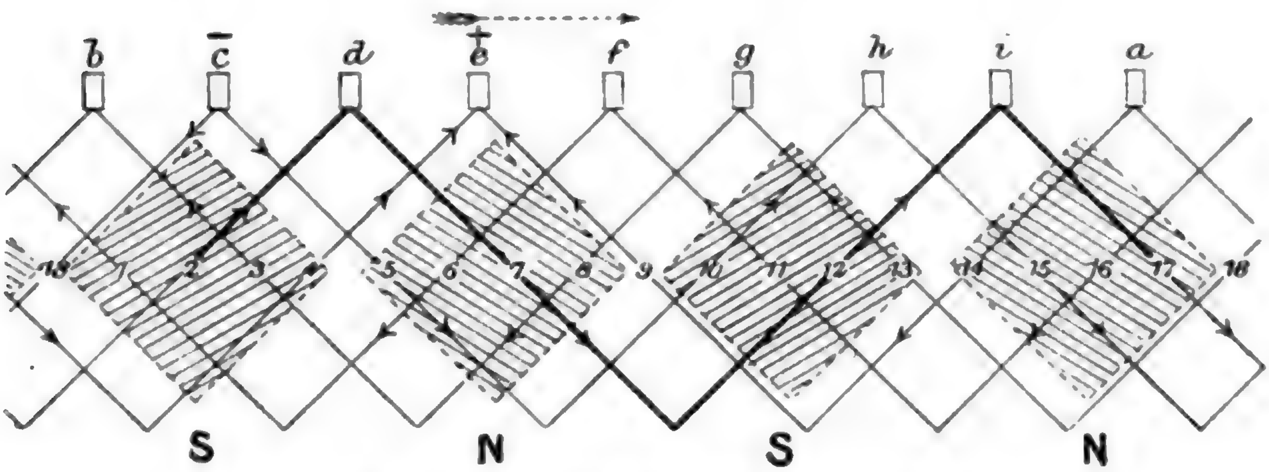


FIG. 189.—FRITSCHE'S OBLIQUE WAVE-WINDING.

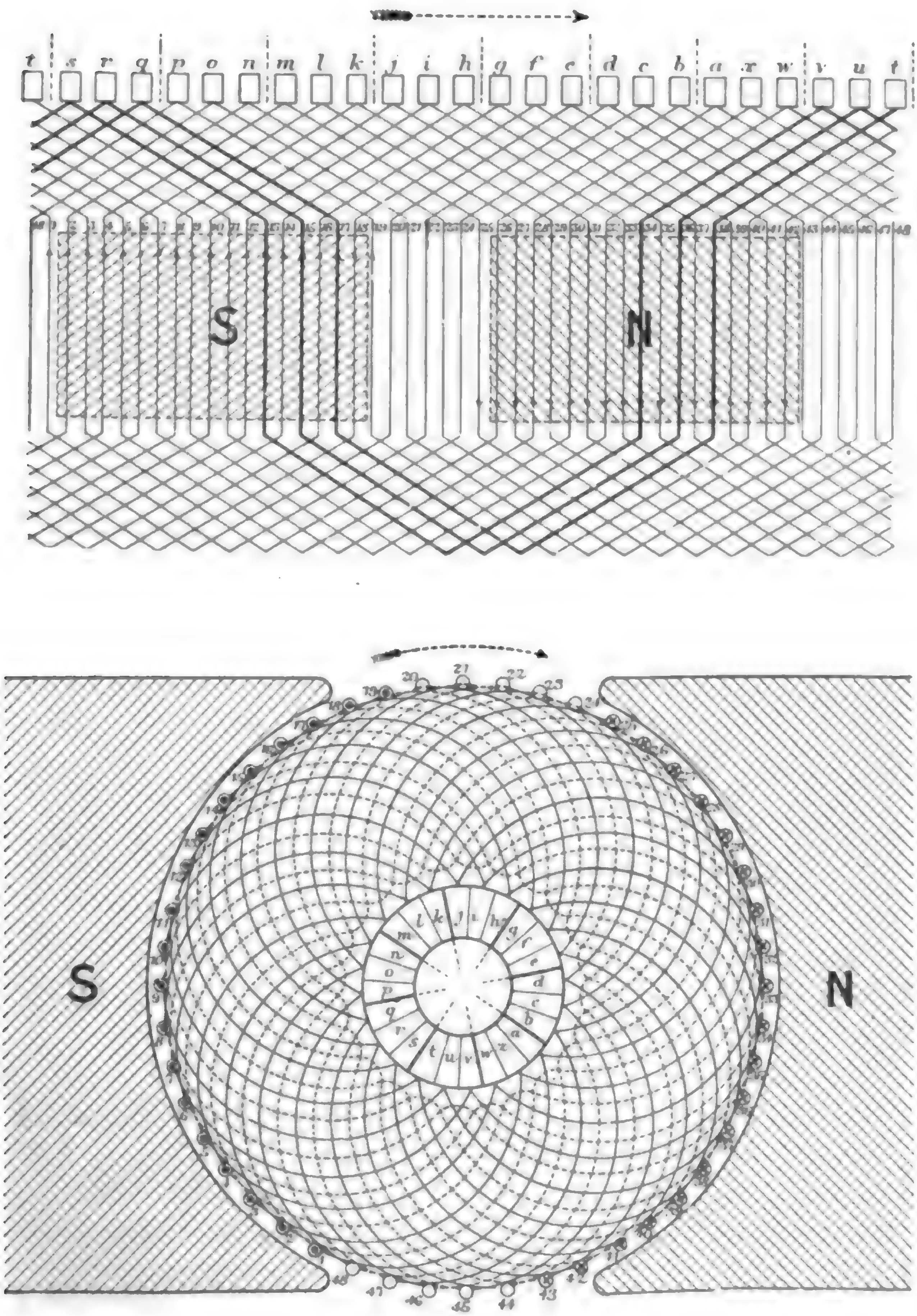
faces. This oblique winding is shown developed in Fig. 189; which should be compared with the winding of Fig. 201, to which it is electrically equivalent.

MULTIPLEX WINDINGS.

In dynamos intended to yield currents so large that a difficulty in commutation is likely to arise, it is convenient to have two or more distinct windings on the armature, each connected to its own set of commutator bars, all the sets being interleaved in one commutator. The current in such cases is collected by a pair of brushes broad enough to make contact over two or three consecutive bars, or by a set of several brushes connected in parallel so as to virtually form broad brushes. The advantage of duplex or triplex windings having two or three independent circuits is that only a fraction of the whole current has to be reversed in the passing of any one bar of the commutator. The division of what would otherwise be very stout conductors into several smaller conductors, also has the effect of reducing eddy-current loss

[1] *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

Figs. 190 and 191 show the connexions of a triplex-wound drum-armature for a 2-pole field having 48 conductors in



FIGS. 190 and 191.—TRIPLEX-WOUND 2-POLE DRUM ARMATURE.

all, that is to say, 16 in each independent circuit. In practice a greater number of conductors would of course be used. Each circuit is wound as an ordinary drum-winding, being connected to 8 bars of the commutator. There are no connexions between the three circuits except such as are made by the brushes, which are broad enough to overlap three bars of the commutator, thus putting the three circuits in parallel.

The winding-tables for this armature are as follows :—

Circuit *a*.				Circuit *b*.				Circuit *c*.			
F	B		F	F	B		F	F	B		F
a	1	22	*d*	*b*	47	20	*e*	*c*	45	18	*f*
d	43	16	*g*	*e*	41	14	*h*	*f*	39	12	*i*
g	37	10	*j*	*h*	35	8	*k*	*i*	33	6	*l*
j	31	4	*m*	*k*	29	2	*n*	*l*	27	48	*o*
m	25	46	*p*	*n*	23	44	*q*	*o*	21	42	*r*
p	19	40	*s*	*q*	17	38	*t*	*r*	15	36	*u*
s	13	34	*v*	*t*	11	32	*w*	*u*	9	30	*x*
v	7	28	*a*	*w*	5	26	*b*	*x*	3	24	*c*

Fig. 192 shows the connexions of a triplex-wound drum-armature for a 4-pole field. The connexions are sufficiently clear without the aid of a winding-table. There are 90 conductors, 30 in each circuit, the spacing being 21.

Multipolar Ring-Windings.

Of these something has been already said on p. 250. It was noted that an ordinary ring placed in a multipolar field would have as many neutral points on its commutator as there are poles around it, and would therefore need as many brushes as the machine had poles. In Plate VIII. are given two views of the large Berlin type of multipolar ring machines with internal field-magnets, which originated with Messrs. Siemens

and Halske. The ring-winding is built up of separate copper conductors which are joined together in a simple continuous spiral. The outer portions of these conductors are made deep and broad, so as to serve as a commutator. The brushes trail on the outer surface of the ring; and it will be noted that there are as many sets of brushes as there are internal poles; the brushes are spaced out at equal angular distances;

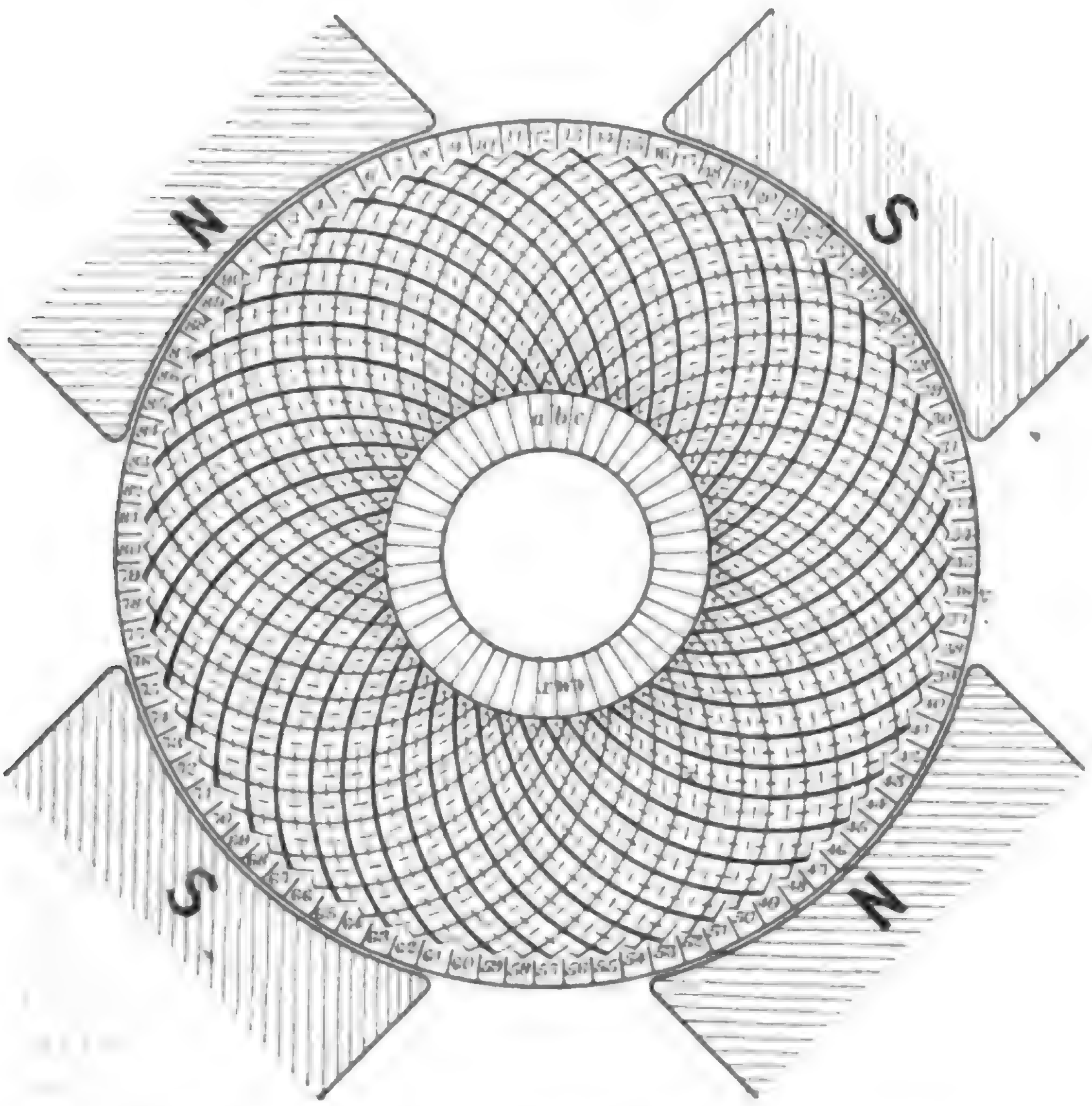


FIG. 192.—TRIPLEX-WOUND 4-POLE DRUM ARMATURE.

there being 10 sets of them, alternately positive and negative. The 5 positive brushes are all connected together electrically; while the 5 negative brushes are also connected together. In this case there are 10 paths through the armature from the + to the − side of the circuit. It is, however, possible to reduce the number of brushes to two, by two independent methods, one of which connects the rows of sections in parallel with

multiple paths throughout the ring, the other puts them in series with but two paths through the ring.

In Fig. 193 is represented a mode of reducing the number of brushes to two, by cross-connecting windings at opposite sides of the ring, a device due to Mr. Mordey. This may be looked upon as simply putting into parallel with one another each coil and the one that occupies the similar place opposite the corresponding pole. The arrangement looks unsymmetrical, but is not really so. For a 6-pole machine each coil would need to be connected with the two others at 120° on either side of it. There are several actual ways of doing this. One is by means of spiral connectors; another is by connecting across the corresponding bars of the commutator. In the Victoria dynamos of the Brush Company (Fig. 283) the length of shaft between the ring and the commutator permits of double cross-connexion, each junction of two adjacent sections being connected by a wire down to the nearest bar of the commutator, and also connected round to that on the opposite side, as in Fig. 194. Such cross-connected machines really have four neutral points on the commutator, but the brushes collect the current from two only.

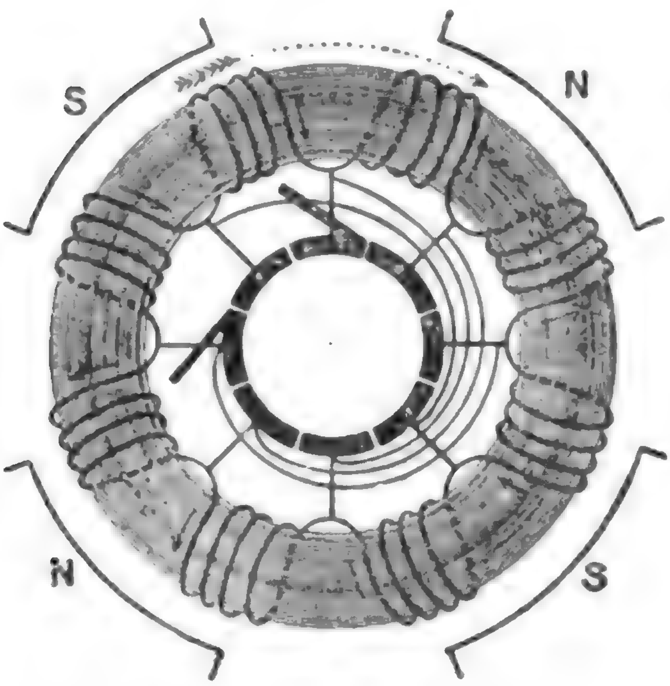


FIG. 193.—MORDEY'S METHOD OF MULTIPOLAR CONNEXIONS OF RING (PARALLEL CONNEXIONS.)

There are several methods of grouping the windings in series so as to gain a double electromotive-force. One of these modes, electrically symmetrical, is depicted in Fig. 195, wherein, while opposite coils are coupled in series, the commutator bars are cross-connected. This requires also but two brushes, at 90° apart. Two other modes of accomplishing the

same end are shown in the windings of Figs. 196 and 197. Here, however, the connexions are not symmetrical, so that the resistances of the two paths (and therefore the respective currents) cannot be at all instants equal.

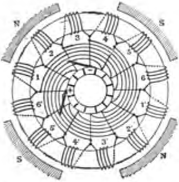


FIG. 194.—CONNEXIONS OF VICTORIA (MORDEY) 4-POLE ARMATURES.

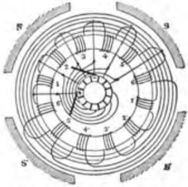


FIG. 195.—4-POLE RING, SERIES GROUPING (2 ROWS).

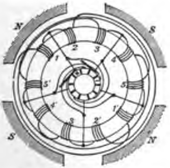


FIG. 196.—4-POLE RING, SERIES GROUPING (2 ROWS).

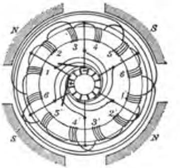


FIG. 197.—4-POLE RING, SERIES GROUPING (2 ROWS).

In yet another arrangement (Fig. 198), each coil is connected down to p segments at intervals of $360° \div p$ around

the ring; and introduces an increased number of bars of the commutator.

Another winding, Fig. 199, devised by Professor Perry, brings down the connexions from each section across a chord of the commutator. The case shown is that of a ring with

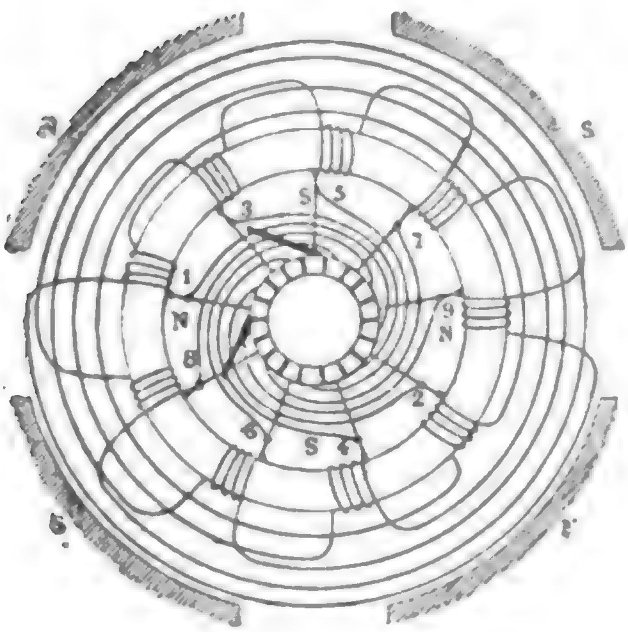


FIG. 198.—MULTIPOLAR RING.

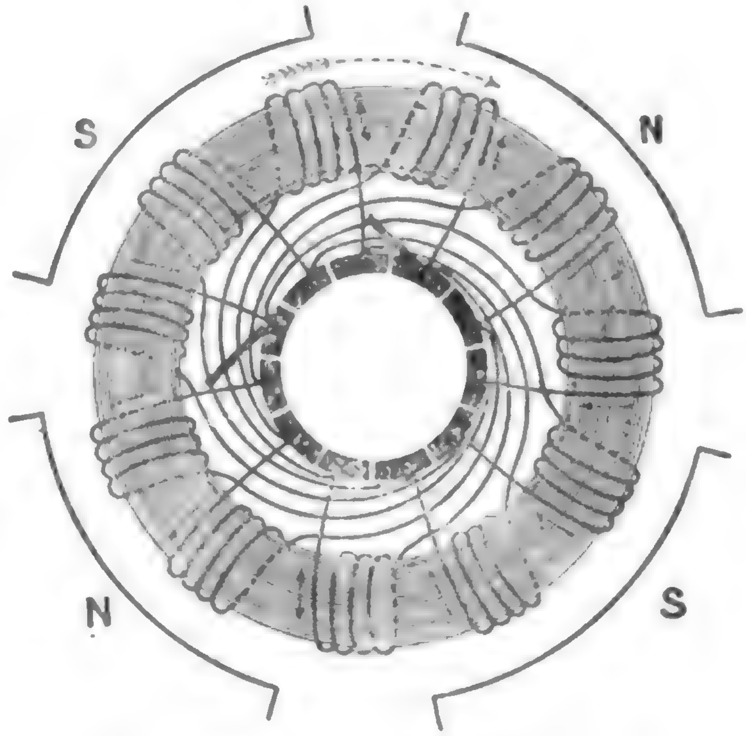


FIG. 199.—PERRY'S METHOD OF MULTIPOLAR SERIES-GROUPING.

eleven sections in a 4-pole field. The number of sections and of parts of the commutator must be odd if the number of pairs of poles is even. It may be either odd or even for 6-pole or 10-pole machines. Arnold points out that it is given by the formula:

$$Z = p y \pm 1.$$

Arnold[1] has described numerous other ring windings of complex kinds; and Parshall has given many examples.

DISK-WINDINGS.

These may in general be treated as drum windings extended radially, the outer periphery corresponding to the back end of the drum. The earliest such winding is that suggested in 1875, by Pacinotti. This is a lap-winding

[1] *Op. citat.*

adapted for a 2-pole field, the **N** pole being behind the upper part, the S pole behind the lower part in the cut. It will be noted that the outer end of each radial conductor is carried round by a peripheral connecting piece to join the end of another radial conductor, which for a 2-pole machine would be the one lying next but one to that which is diametrically opposite. The schematic figure relates to a 10-part armature, made up of twenty radial conductors. They are numbered so that the order of connexions may be traced. The diameter of commutation being *d d*, the currents flow radially inwards in one half and radially outwards in the

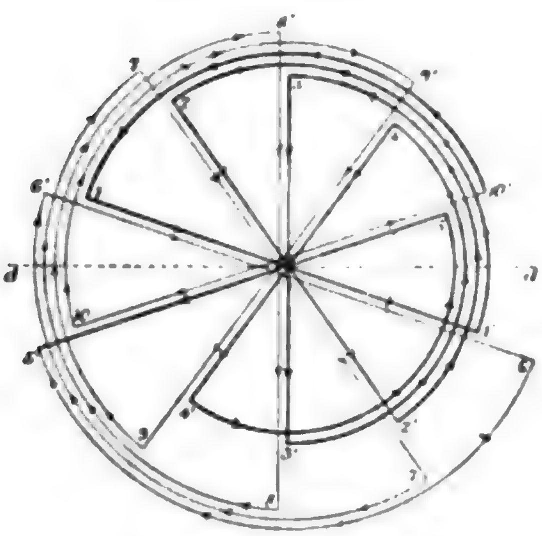


FIG. 200.—PACINOTTI'S DISK ARMATURE.

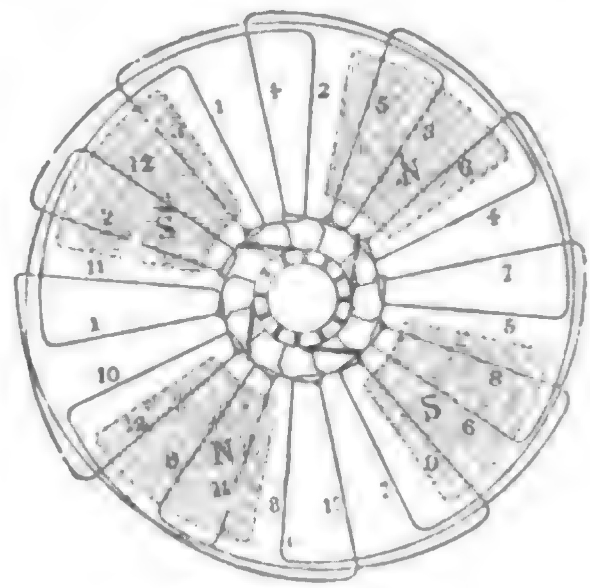


FIG. 201.—4-POLE DISK LAP-WINDING.

other half of this disk. The construction of Pacinotti's experimental machines is described in his original paper.

Since then many suggestions have been made for windings of this description.

A lap-winding, identical with Pacinotti's, but adapted to a 4-pole field, is depicted in Fig. 201; it is known as the Edison "new disk" winding. The disk-armatures of Hookham's electricity meters are also lap-wound. Bollman and Müller have devised multipolar disks with wave-winding.

Fig. 202 shows the connexions of a disk armature designed by Müller[1] for a 4-pole machine in which the conductors

[1] U.S. Patent, 331726 of 1885.

passing in front of the different pairs of poles are placed in series. The brushes in this case are placed at 90° to each other.

Disk-armatures have been revived by Desroziers and Fritsche. Desroziers employs for a 6-pole machine the elaborate wave-winding shown in Fig. 203. A special study of this class of winding has been made by Arnoux.[1] Fritsche

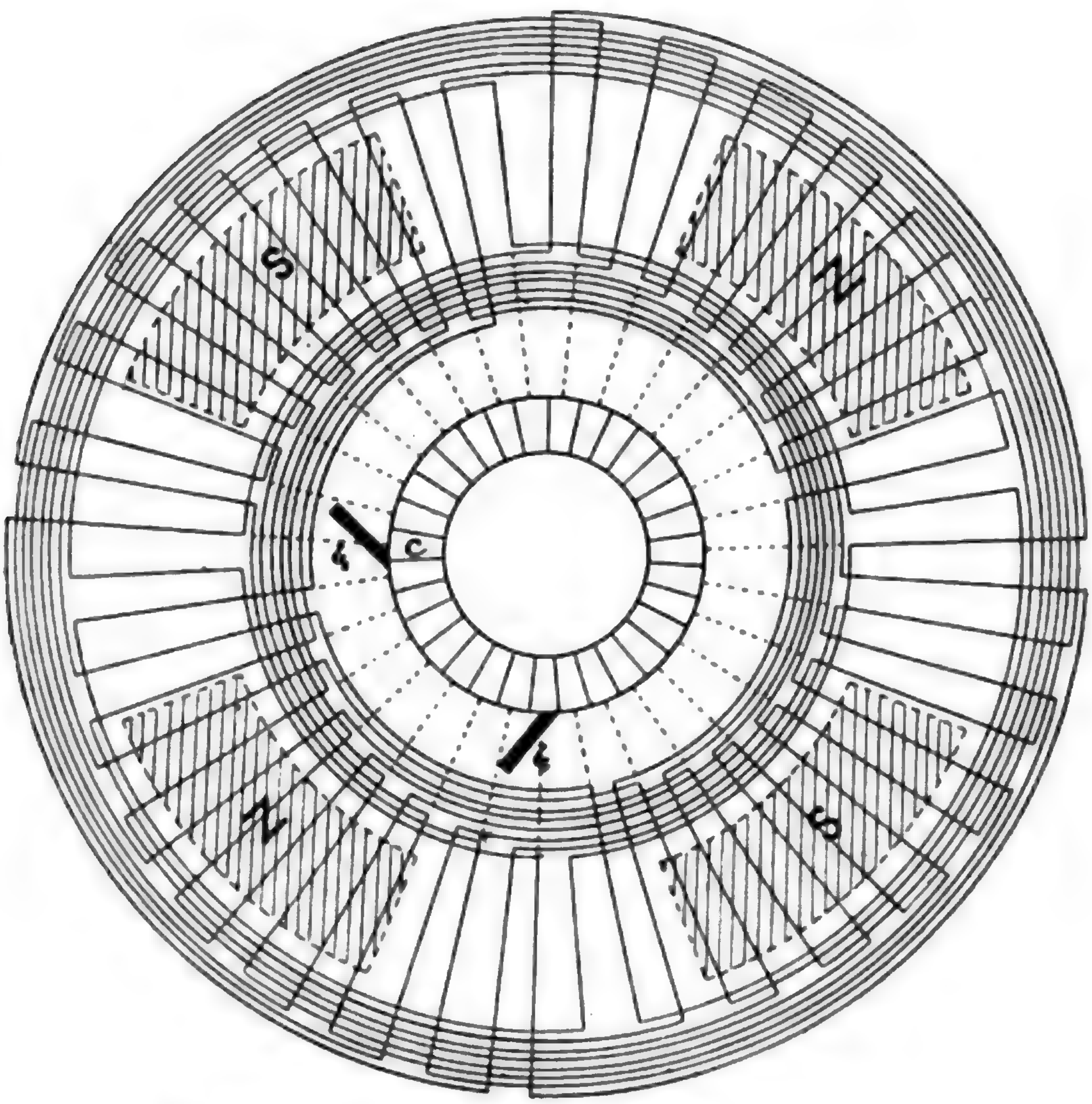


FIG. 202.—4-POLE WAVE-WINDING (MÜLLER).

employs polygonal poles, enabling him to use, as conductors, strips of metal built up in star-polygon fashion without any radial parts—a structural advantage. His disk, if developed out straight, would, for a 4-pole machine, be adequately represented by Fig. 189, p. 272. The two sets of conductors constitute two layers which are united at their outer ends to the bars of a commutator at the outer periphery.

[1] See reference, p. 244.

The main difficulty in the employment of disk-armatures has been in the construction of an armature of this sort which is mechanically strong and capable of resisting wear and tear. Desroziers has done much to overcome this difficulty, and has produced machines which are very widely used in France and her colonies. He discerned that a disk-armature can be separated into two parts; that is to say, taking the alternate

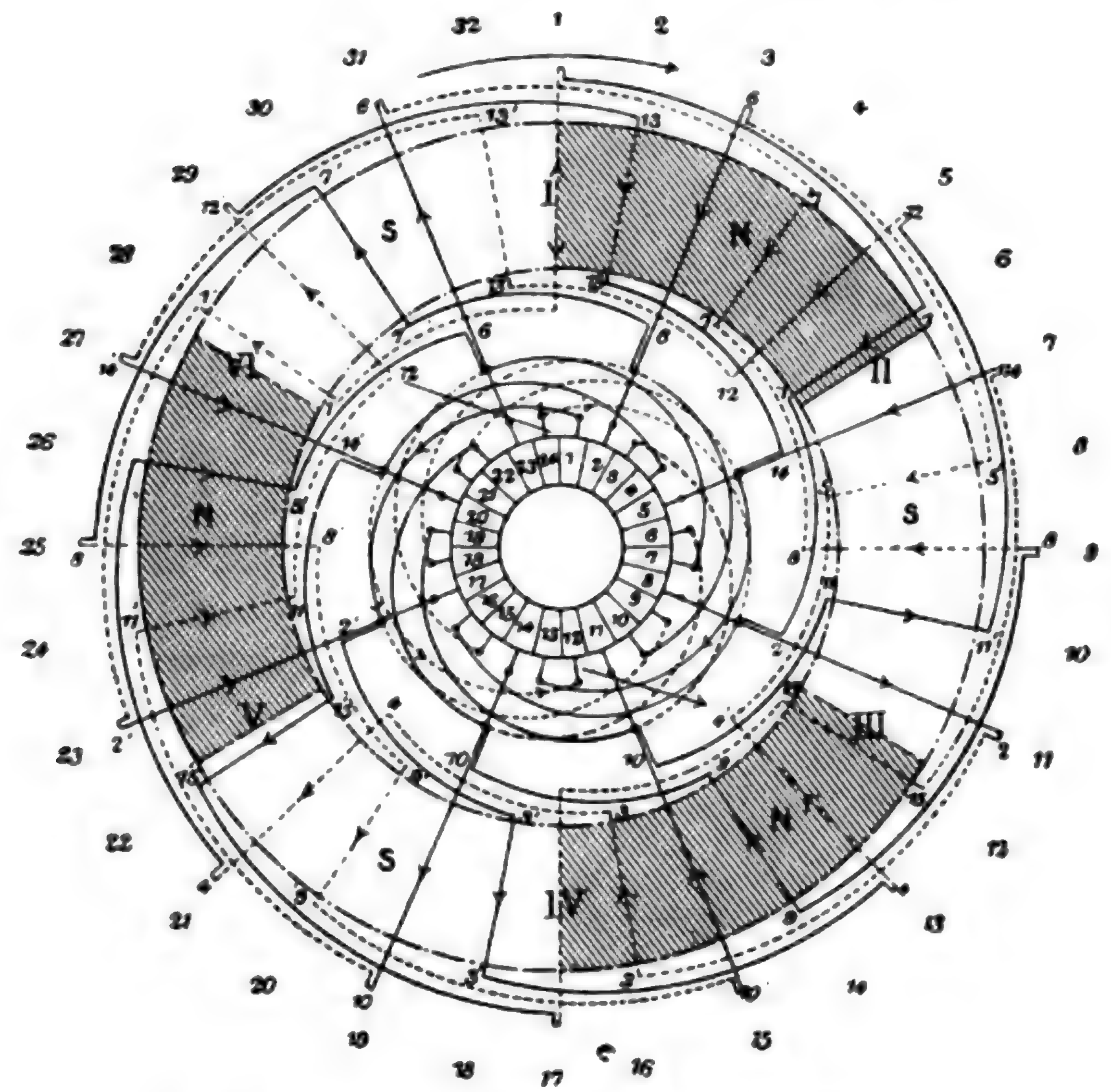


FIG. 203—DESROZIERS' 6-POLE DISK-WINDING.

radiating conductors (the odd numbers for example), it is possible to build them and their connectors into a regular figure in one plane without troublesome over-crossings, and this plane of conductors can be superimposed upon a similar one built up of the other alternate conductors, so that the ends of the connectors coincide and only require to be soldered together to form a complete re-entrant winding.

This will be understood by reference to Figs. 204, 205 and 206. Fig. 204 shows six conductors joined in series forming part of a disk armature intended for a 6-pole field, the current flowing inwards when passing one pole and outwards when passing the next pole of opposite sign. In order to mount a number of these conductors in series, they and their connectors may be taken in pairs and half of them mounted in the manner shown in Fig. 205, in which the portion R *c d h t* will be recognised from Fig. 204. The other half are mounted as in Fig. 206,

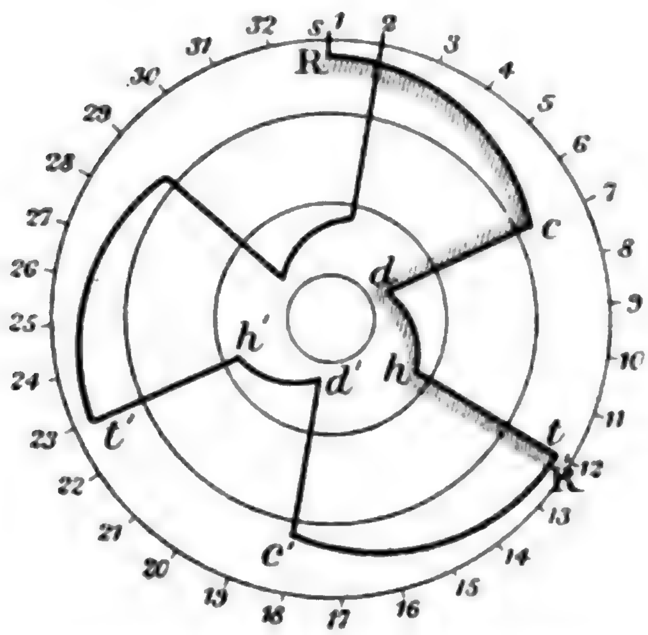
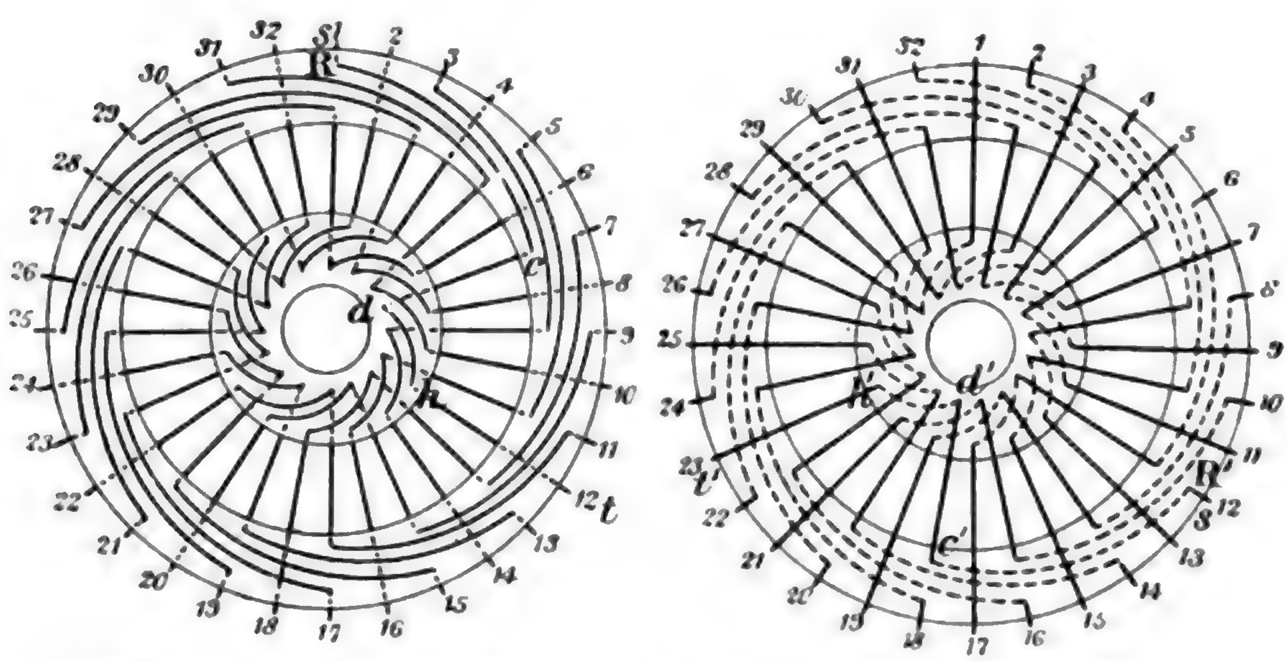


FIG. 204.—SKELETON DESROZIERS' WINDING.

where the portion R' *c' d' h' t'* is a continuation of the series in Fig. 204. In each of these planes of conductors the



FIGS. 205 AND 206.—CONSTRUCTION OF DESROZIERS' DISK ARMATURE.

ends are brought out to the points numbered 1, 2, 3, &c., up to 32. By placing these two disks face to face, then

soldering up the coinciding ends and carrying those on the inside to the bars of a commutator we have a complete armature winding.

It is obvious that there are other ways of dividing up the series of conductors shown in Fig. 204 than the method adopted in Figs. 205 and 206. For instance, all parts similar to R *c d*, R′ *c′ d′*, &c., might be mounted to form one plane of conductors and the parts *d h t*, *d′ h′ t′*, &c. would then form the other plane. In high voltage machines where a number of turns per segment are required, this can be done in the manner shown in Fig. 207, where the same letters are used to denote corresponding parts.

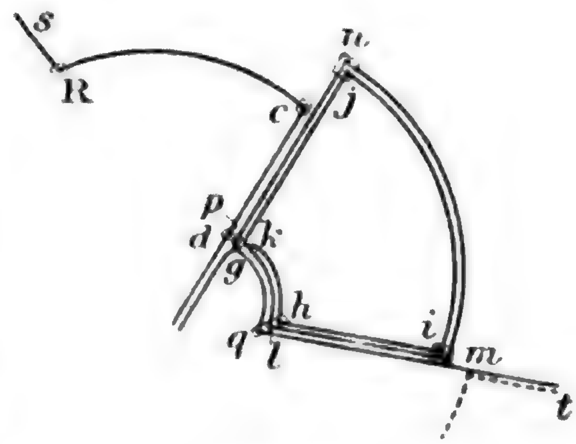


FIG. 207.

In practice there are two distinct methods of construction used: (1) wire-wound armature; and (2) strip-built armatures. The wire in the former is threaded through holes in two concentric compressed cardboard rings that form the outer and inner supports for each plane of conductors. The two planes are then mounted face to face on a metal spider, the arms of which, radiating from the shaft, pass between the two layers of conductors.[1] Large machines of this type can be made which do not weigh more than 55 lbs. per horse-power. The efficiency is as high as that of good continuous-current machines of the ordinary type with cored armatures.

[1] For further particulars of these machines see *Electrical Engineer* (N.Y.), xvi. 259.

CHAPTER XIII.

PRACTICAL CONSTRUCTION OF ARMATURES.

LITTLE has yet been said about the proper modes of securing the armature-conductors, of insulating them, and of ventilating them. Most, though by no means the whole, of the present chapter relates to continuous-current dynamos and motors; but much of it is equally applicable to alternators. Broadly, armatures having cores of iron may be grouped in two classes; those which have *surface windings* supported on smooth cores, and those which have *sunk windings* laid in slots or holes in the cores.

Armature Cores.—Cores are always laminated, being constructed either of (1) sheet-iron *disks*, (2) iron *ribbon*, or (3) iron *wire*. Ribbon is only used for discoidal armatures magnetized through the flanks. For drums and elongated rings, disks stamped out from soft sheet iron, or from the best "mild steel," are almost universal. The usual thickness is from 1 to 2 mm. (*i. e.* from 40 to 80 mils), but some makers go down to 14 mils. They should be of brands showing the least hysteresis. After being stamped out they should be annealed, and the burr at the edges removed. At this stage, if the cores are smooth (not toothed) it is usual to assemble them upon the shaft, turn them down truly in the lathe, then take them apart and remove the burr by grinding lightly on an emery wheel, then re-mount them. Before being finally mounted on the shaft they must be lightly insulated one from the other. For this purpose it is usual either to cover one face of each core-disk with varnished paper, or to enamel both faces of each core-disk. Mica insulation here would be too expensive, and is not necessary. It is usual to make the two end core-disks of stronger iron, sometimes as much as

12 mm. or ½-inch thick. For discoidal armatures the iron ribbon must be insulated with an interposed band of varnished paper. To stiffen a discoidal armature-core it is usual to build it upon a foundation ring of soft iron, and this in some cases is constructed with a projecting central iron web, on either side of which iron ribbon is coiled. An example is afforded by the core of the Victoria (Mordey) machine, Fig. 283, p. 418.

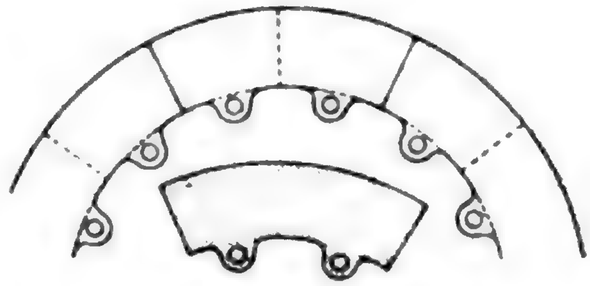


FIG. 208.—SEGMENTAL CORE-DISKS (KAPP).

For large machines the core-disks are built up in segmental portions to reduce cost. The cores are constructed, as shown in Fig. 208, of pieces which overlap in successive layers, each piece having eye-holes for bolts.

Wire cores were at one time largely in vogue, having been used by Gramme. The soft iron wire, varnished or slightly oxidised on its surface, was wound on a special former, then removed, taped externally, and wound with the copper wire conductors. Wire cores have three disadvantages: (i.) they are mechanically less satisfactory than disk cores; (ii.) they fill a given core-space with an actually less nett cross-section of iron owing to the interstices between the separate wires, only about three-fourths of the total cross-section being occupied by iron; and (iii.) they present a discontinuity radially which offers an unnecessary reluctance in the path of the magnetic lines. The substitution of a square iron wire for a round one, is an improvement in all these respects.

Another mode of constructing wire cores was presented in the armature of the Bürgin machine, which originally consisted of several rings set aside by side on one spindle, these rings being made of iron wire wound upon a square frame, and carrying each four coils. Mr. Crompton changed the square form to a hexagon having six coils upon it and increased the number of rings to ten. This form, however, proved to be in no way superior to an ordinary Gramme armature.

Toothed Cores.—Pacinotti's armature of 1864 (Fig. 211) was a toothed ring of solid iron supported on brass spokes and having boxwood distance-pieces fixed to the teeth to hold the windings apart. Armatures built up of toothed core-disks, consistently advocated by the author for the past twelve years, have been much used in recent time. They have four advantages over smooth armatures. (i.) The teeth present an excellent means of driving the copper conductors which lie between them; (ii.) the teeth may be brought very close to the polar surfaces of the field-magnet, with very narrow

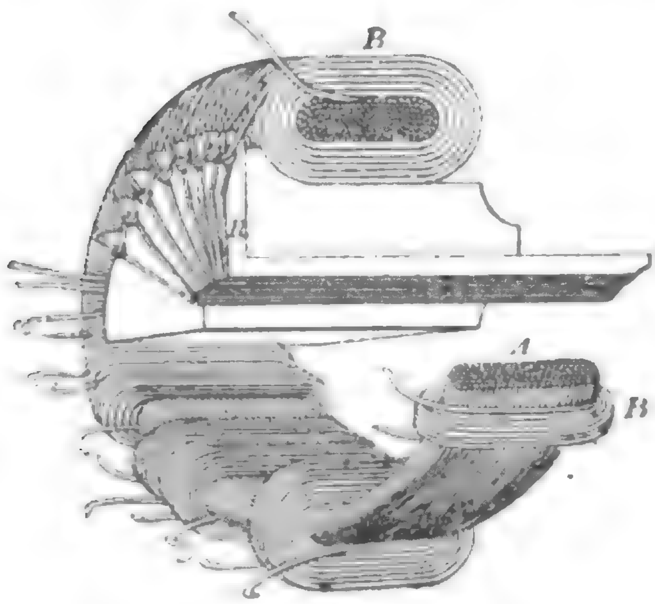


Fig. 209.—Gramme Ring with Wire Core.

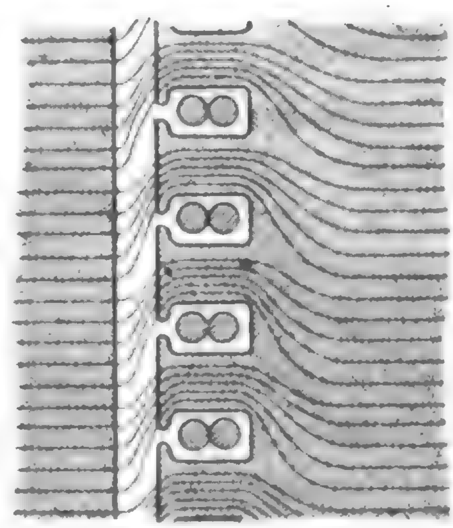


Fig. 210.—Sunk Winding and Magnetic Drag on Teeth.

clearance, thus bettering the magnetic circuit and therefore reducing the amount of copper required to excite the magnetic flux; (iii.) the drag comes almost entirely on the iron cores instead of on the copper conductors, as indicated in Fig. 210; (iv.) if the slots are deep the conductors are largely protected against eddy-currents. To set against these real advantages are the disadvantages of somewhat greater labour required in milling out the channels between the teeth of the assembled core; the extra difficulty of insulating the core from the conductors; and the liability of the teeth to set up eddy-currents (see p. 93) in the polar faces. The latter can be cured by making the teeth numerous and narrow, also by laminating the polar faces with grooves, and by enlarging the clearance.

Or by finally serving the entire armature outside the copper conductors with a layer of iron wire.

Toothed armatures were at one time much used by Messrs. Paterson and Cooper; but English makers generally

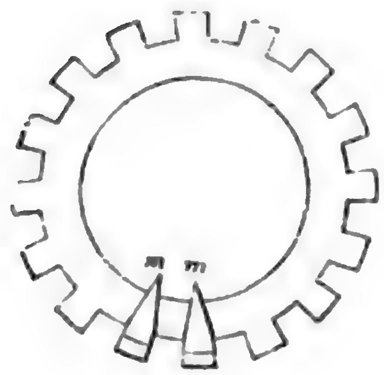


FIG. 211.—PACINOTTI'S TOOTHED RING ARMATURE (1864).

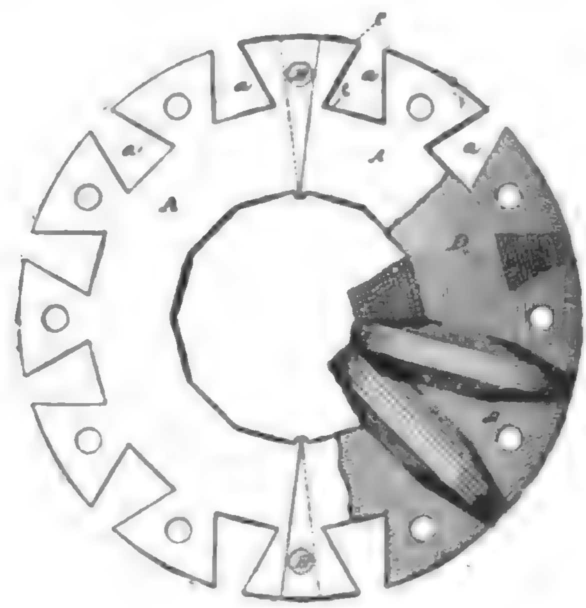
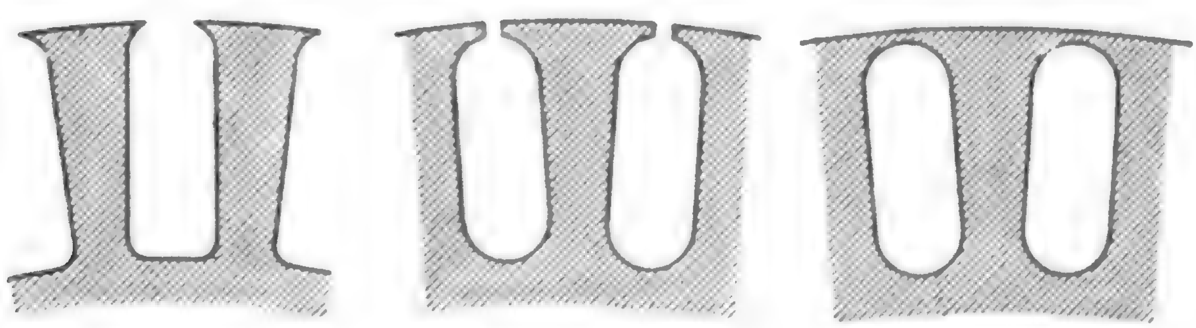


FIG. 212.—CORE OF ARMATURE OF MOTOR (CROCKER-WHEELER).

have preferred smooth cores. In the United States, however, the smooth core is the exception and the toothed core the rule. Fig. 212 shows the form of armature core used in the small Crocker-Wheeler motor (Fig. 341). The core-disks are made, for convenience of winding, in two halves.



FIGS 213, 214, 215.—TOOTHED AND SLOTTED CORE-PLATES.

Straight teeth (like Fig. 211) and triangular teeth (like Fig. 212) are, however, the exception. They are more usually T-shaped, and with rather deep slots between the teeth, as indicated in Fig. 213. Sometimes they are preferred in the

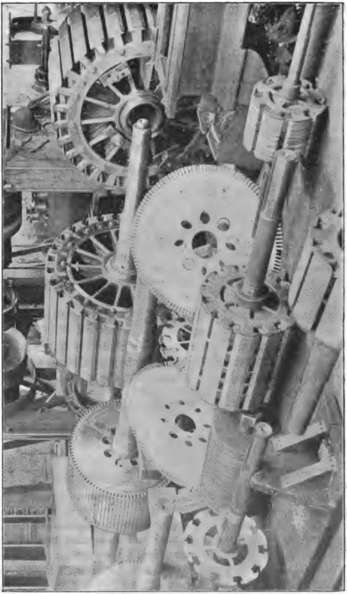


Fig. 216.—Group of Core-Disks (Westinghouse Electric Co.).

form of Fig. 214, which shows the slot as an oblong perforation with a narrow opening only at the periphery. Fig. 216 depicts a group of armature cores and disks in the shops of the

FIG. 217.—WIRING DRUM-ARMATURES (WESTINGHOUSE ELECTRIC CO.).

Westinghouse Company at Pittsburg. The cores with large T-shaped teeth are for alternators; whilst the cores with numerous narrow teeth are for continuous-current dynamos or motors. After the core-disks have been assembled on the shaft, the slots are very carefully filed out or reamed out, to avoid projecting edges that might cut the insulation. The mode of drawing in the insulated conductors of drum-armatures is shown in Fig. 217. In the armature which is being wired the slots are deep enough to admit of four conductors one above the other: this being intended for a high voltage winding. Compare also Fig. 347. With T-shaped teeth it is not necessary to apply binding-wires externally, the conductors being secured by driving a long wooden key into the slot after the wires have been inserted.

Pierced Core-disks.—The advantages offered by toothed core-disks are possessed to a still higher degree by core-disks pierced with apertures just within the periphery. Such were independently suggested by Parsons, by Swinburne and by Brown. Wenström suggested slotted holes. In such armatures the conductors are carried in tubes of insulating material that pass through the perforations. This construction is eminently satisfactory from the mechanical and magnetic point of view. One peculiar and valuable property of the pierced core-disks is, that they completely protect the embedded copper conductors, however massive, from parasitical eddy-currents which would otherwise be generated in them. The slots are often made oblong, as in Fig. 215, instead of circular. The standard style of hole used by Brown is about 50 millimetres long by 20 millimetres broad.

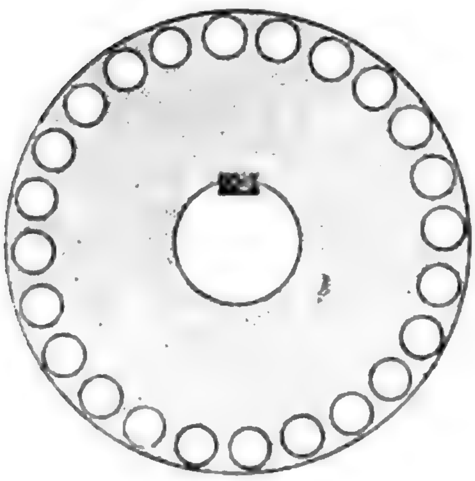


FIG. 218.
PIERCED CORE-DISK.

Driving-Spokes and Spiders.—Armature cores are usually built up upon an internal frame or skeleton pulley firmly keyed to the shaft. In small drum-armatures this internal

supporting frame may be omitted, the core-disks themselves being keyed directly on to the shaft. Some makers punch hexagonal holes in the core-disks and thread them on over a hexagonal shaft.

Frequently the core-disks are held together by insulated bolts passing through them, and driven by spiders keyed to the shaft, as in Fig. 219. To this construction there is the objection that the bolt-holes reduce the effective cross-section of iron and strangle the magnetic flux. It is also needful that the bolts should be insulated from the arms of the spiders by ebonite washers and bushes, otherwise the framework will

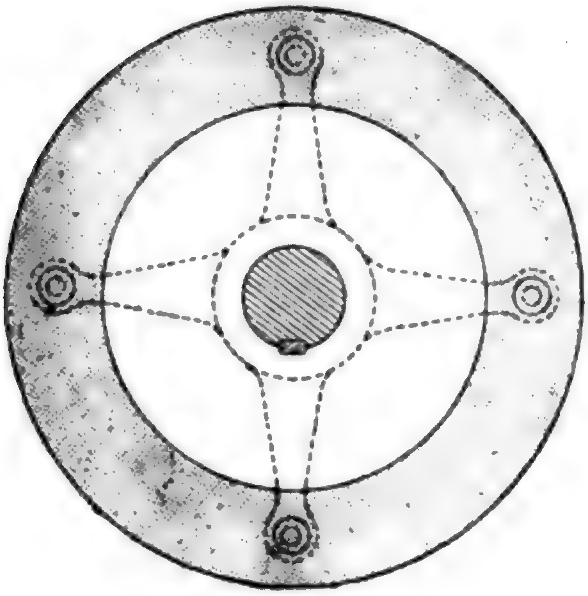


FIG. 219.—MODE OF DRIVING CORE-DISK.

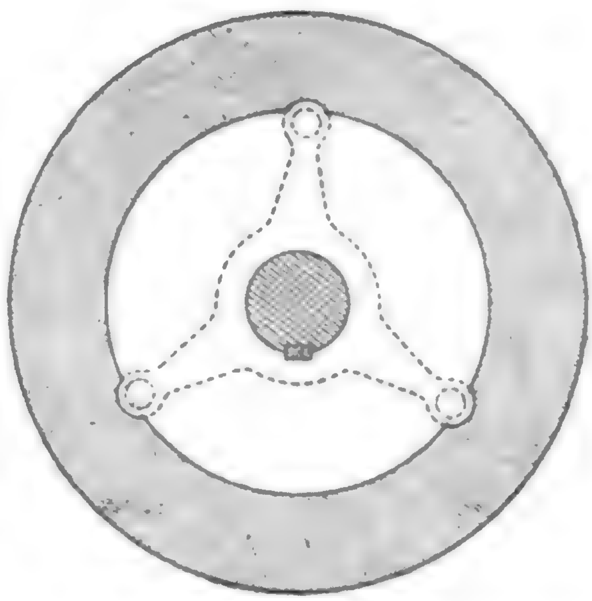


FIG. 220.—PATERSON AND COOPER'S MODE OF DRIVING CORE-DISKS.

constitute a closed circuit for eddy-currents which will heat it. A better mode is that used by Messrs. Paterson & Cooper, Fig. 220, in which the section of the iron is but slightly reduced and the bolts are entirely internal to the core.

Another mode is to provide the core-disks with dovetail notches into which pass long flanges from the shaft. Mr. Crompton, who introduced this construction in 1886, also used a method of connecting with the driving shaft by three grooves in the latter. In another form, a ribbed sleeve, which slips over the cylindrical shaft, is driven by a long feather. It is less costly and equally mechanical. Another form has the four projecting flanges in one solid structure.

Kapp's mode of driving the core-disks is shown in Fig. 221, which should be compared with Plates I. and II. Over the shaft is slipped a long sleeve provided with three projecting flanges to support the core-disks. This sleeve, which is prevented from slipping by a long feather slightly sunk into a key-way, has the advantage of stiffening the shaft. In armatures for ring-winding, this internal structure is of gun-metal; in those for drum-winding, of cast iron. It is pushed up towards a face-plate which rests against a shoulder on the shaft, and the core-disks are tightened together between the

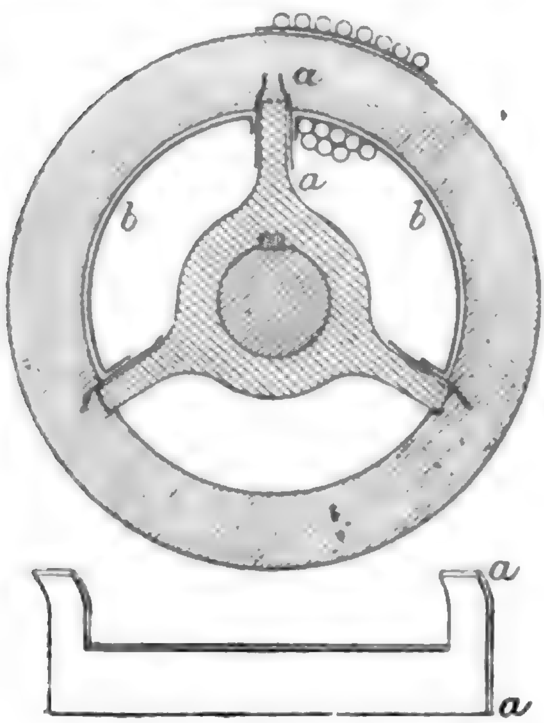


FIG. 221.—KAPP'S MODE OF DRIVING CORE-DISKS.

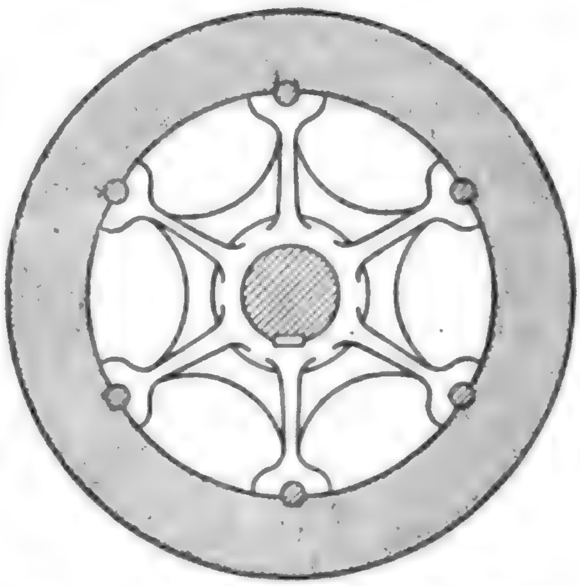


FIG. 222.—BROWN'S LATEST MODE OF DRIVING CORE-DISKS BY MEANS OF KEY-BOLTS.

two face-plates by a nut on the shaft. The lower figure shows the form of the strips of fibre used for insulating.

Figs. 222 and 223 show Brown's modes of supporting and driving core-disks. Fig. 223 corresponds with Plate VII.

In Fig. 223, the spiders are two in number, each having four internal web-spokes and wide end-flanges. They fit over the shaft, with feathers to prevent turning. One of them is held up against a shoulder on the shaft, and after the core-disks have been assembled, the other one is pressed up by a large hexagonal nut. It will be noticed that two of the webs on each spider are ribbed; the core-disks being stamped with

notches to prevent them turning. Of the four web-spokes two are long and two short, so that the core-disks may be compressed as the spiders are forced together. Many makers now use similar arrangements.

In Fig. 222, which is more recent, round steel keys are driven into grooves cut in the ends of the spider flanges, and in the core-rings.

The use of stout end-plates drawn together with screw bolts to compress the core-disks is also illustrated in Brown's machine, built by the Oerlikon Co., Plate IV.

FIG. 223.—BROWN'S MODE OF DRIVING THE CORE-DISKS.

Another arrangement, admirable for its strength, is shown in Fig. 224. Upon the shaft are placed two gun-metal cones, with shallow feathers to prevent turning. In each cone are cut three slots at angles of 120°, the bottoms of the slots also sloping cone-wise. Into these slots fit three bridge-like gun-metal flanges, with projecting lugs at their ends, to hold up the core-disks. By screwing up a nut on the shaft the cones are pressed together, and thereby the three flange-spokes are

forced outwards and support the core-disks at three points of their internal periphery.

Another mode, shown in Plate X., is applicable to armatures of large diameter; the core-plates have internal notches to receive the ribs of the driving centre.

It should not be forgotten that compressing stresses diminish the magnetic permeability of iron in the direction of the stress; and that tensile stresses increase the permeability.

Insulation of Iron Cores.—Mention has been made of the proper mode of insulating the core-disks internally from one

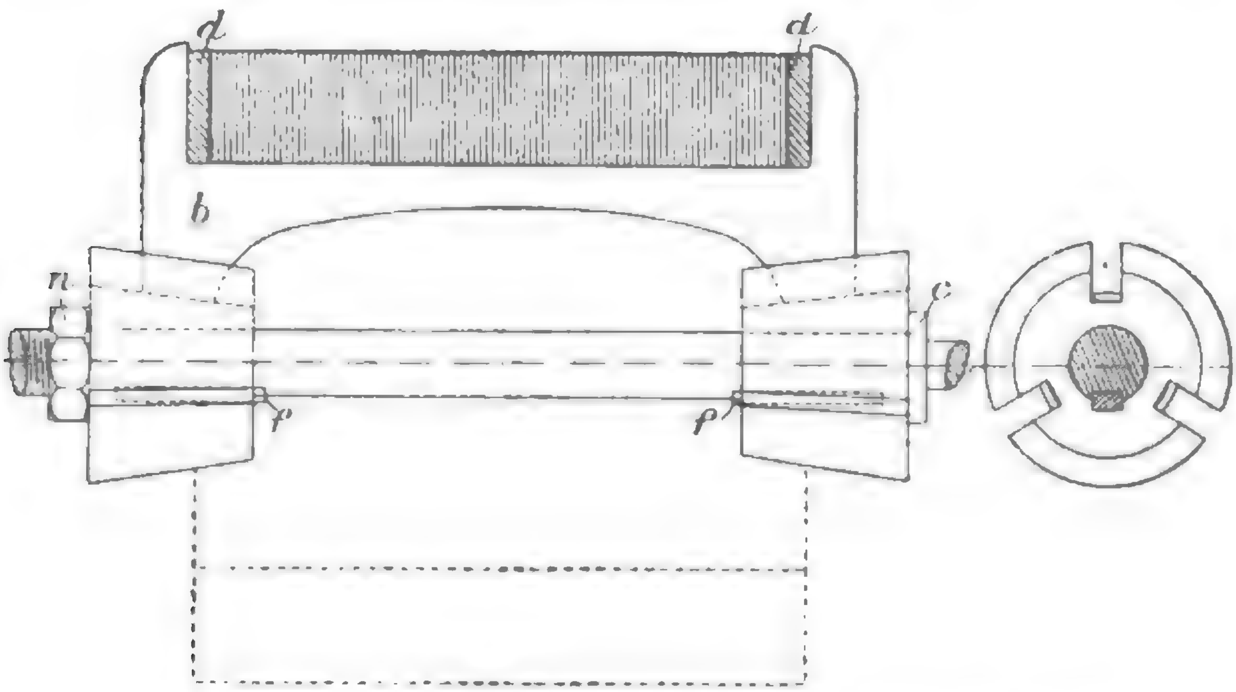


FIG. 224.—IMMISCH'S METHOD OF DRIVING BY TWO CONES.

another by interposing paper or enamel. At their peripheries they must be prevented from making metallic contacts with one another. But beside this internal insulation, they must be protected very carefully from *external* contact with the copper conductors. In the case of smooth cores it is usual to serve the completed core with one or two coats of enamel or japan, and then to cover it with a layer of some tough material such as canvas, manilla-paper, or Willesden-paper, well varnished with shellac varnish or with Scott's rubber varnish. Where toothed cores are used, channels of varnished paper, or of paper with mica strips laid between, are inserted between the teeth. In the case of cores for ring-winding,

particular care must be taken to insulate the inner periphery and the driving spokes, where the internal windings lie near them.

Ventilation of Armatures.—Armature cores heat from three causes: hysteresis; eddy currents; and heat derived from the copper conductors. The careful lamination and insulation described above, are but means to prevent waste of power and to avoid risk of overheating. In the case of ring-wound machines there is usually an amount of surface exposed sufficient to get rid of the heat generated in the conductors without resorting to any special mode of ventilating. But in the case of large and solidly constructed drum-armatures, some mode of forcing the ventilation may be necessary. In drum armatures with the old-fashioned wire-windings overlapping the ends, adequate ventilation is impossible. As examples of ventilated cores the reader should see Kapp's drum-armature, Plate II., Fig. 1, and Brown's drum-armature, Plate VII. There are special ventilating ducts in the armature of the large street-tramway generator, Plate X.

In the case of drum-windings having end-connexions built up, the arrangements with one set of evolute spirals and one set of straight radial pieces (as in Fig. 177, p. 263) are sometimes preferred to those with two sets of spirals as in Fig. 179, p. 264, as having a better fan action. Some makers use spiders with arms sloped like the sails of a windmill, so as to propel air through the interior of the armature.

Balancing of Armatures.—It is very needful that armatures should be properly balanced, otherwise they will set up injurious vibrations in running. Most makers test their armatures for balance by laying the journals on two parallel metal rails (or "knife-edges") and noting whether the armature will remain in any position without tending to roll. It is well indeed to balance them thus on completing the core ready for winding, and again after winding. If the end core-disks have been made of thick iron, holes can be drilled in these to restore perfect balance; or leaden plugs can be inserted.

It may be remarked that this mode of observing the statical balance is not perfect; for if the masses that balance

around the axis are distributed unsymmetrically along the axis, there will be, when running, a tendency to vibration.

Driving-Horns.—It is of primary importance that the armature conductors should be properly driven, otherwise they may be raked out of place by the tangential drag in the magnetic field (p. 99). In the case of ring-windings, such injurious action is less likely to occur than with drum-windings, as the convolutions which thread through the interior of the core tend to bind, and press against the driving-spokes. But even here, it is found needful to provide positive driving at a number of points around the periphery. Crompton found it needful to drive boxwood wedges in between the core-disks. He then adopted a construction in which pieces of fibre are inserted at intervals for ventilation between the core-disks; the gaps so left being convenient for the insertion of driving-horns between the wires. Kapp used projecting narrow steel horns protected by pieces of hard fibre. Goolden used strips of hard white fibre inserted into shallow keyways milled out of the surface of the core and held in by external binding-wires. For discoidal armatures the driving-horns must project at the flanks, being inserted between the core-ribbons.

Binding-Wires.—In the case of smooth cores the conductors must be secured in their places by a number of external bands, known as *binding-wires.* These must be very strong, to resist centrifugal force and to hold the conductors from being dragged aside; and yet at the same time must occupy very little radial depth, that the clearance between conductors and pole-face may be as narrow as possible. The almost invariable practice is to employ a tinned wire, of hard-drawn brass or steel, which, after winding, can be sweated together with solder into a continuous band. It is impossible to give rules for the sizes of binding-wires. A frequent size for steel wire is 40 mil, or a little under 1 mm. diameter. The wire is wound on in bands of from 10 to 30 turns each, the separate bands being spaced out at distances of from 1 to 2 inches apart. Under each belt of binding-wires a band of insulation must be laid. This usually consists of two layers; first a strip of thin vulcanised fibre slightly wider than the

band of wires, and then a strip of mica (in short pieces) of about equal width. Some makers lay a small strap of thin brass under each band of binding-wires, having ends which can be turned over and soldered down to secure the two ends of the wire from flying out. The armature depicted in Fig. 225 is a drum-armature, having six sets of binding-wires. As an example it may be stated that Mr. Esson recommends for a smooth drum-armature 10 inches in diameter and 12 inches in length, six bands of 18-mil (*i. e.* No. 26 B.W.G.) wire, each band being about $\frac{5}{8}$ inch wide, and containing about 33 turns; the bands being, therefore, rather less than $1\frac{1}{2}$ inches apart. On a drum or ring 20 inches in diameter he would use 35-mil wire, in bands $\frac{1}{2}$ inch wide, about 2 inches apart.

In the standard multipolar dynamos of the General Electric Co. (see Fig. 292), phosphor-bronze bands are now used instead of binding-wires.

In the following table are given the particulars of the bindings adopted in some of the smooth-core drum armatures of the Edison standard bipolar dynamos.

Output of dynamo in kilowatts	1	10	30	50	150
Revolutions per minute	2100	1600	1200	700	450
Length of armature body (inches)	$6\frac{1}{2}$	12	18	$24\frac{1}{2}$	$26\frac{1}{2}$
Diameter of armature body	$3\frac{1}{2}$	$6\frac{1}{4}$	$9\frac{3}{16}$	$12\frac{15}{16}$	$23\frac{3}{4}$
No. of binding bands on body..	6	7	9	13	7
No. of strands in each band	22	19	21	18	24
Gauge of brass binding-wire (B.W.G.) ..	25	23	21	19	19
Width of mica underlay 0·01 inch thick	$\frac{5}{8}$	1	1	$1\frac{1}{8}$	$1\frac{1}{2}$
Number of clamps (of copper sheet, 14 mils thick and $\frac{1}{8}$ to $\frac{1}{4}$-inch wide) on each band	2	3	4	4	6

Winding Armatures.—Given a scheme of winding according to any of the modes discussed in Chapter XII., the problem remains how to carry it out in the factory. Ring-windings may be considered first, then drum-windings. A broad distinction may be set up between wire-wound armatures and those with built-up windings consisting of bars and

connectors, or of specially constructed portions that are put together instead of being wound on. Wire-wound armatures are usual for outputs below 100 amperes, including all arc-lighting machines. Single round wire, insulated with double cotton covering soaked afterwards with shellac varnish, is usually adopted for small machines and arc-lighting dynamos. Silk-covered wire is rarely used. For small electroplating dynamos it is frequent to use several round wires in parallel, even to as many as twenty or thirty separate wires side by side. Wire-drawers will furnish rectangular wire of any desired

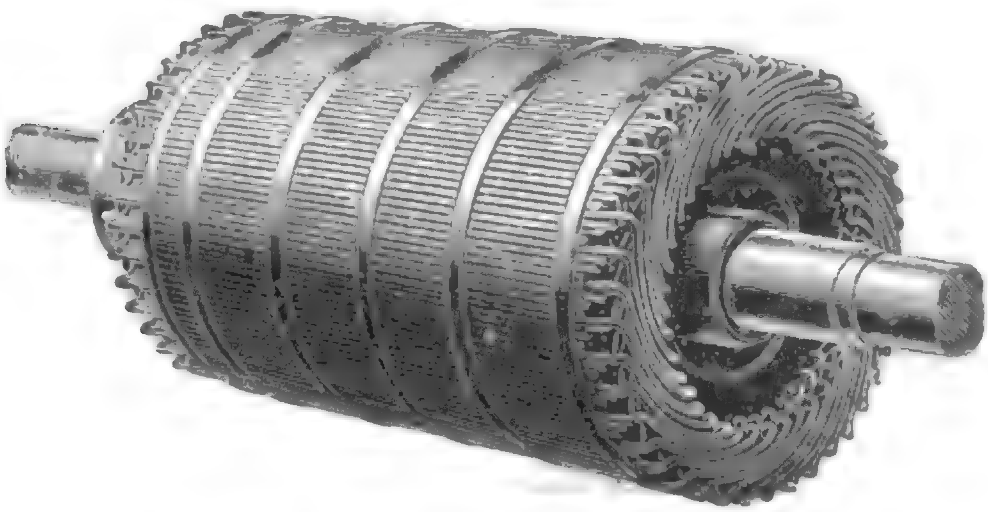


FIG. 225.—ALIOTH'S DRUM-ARMATURE.

section; but for greater flexibility in winding, a rectangular conductor made of three or four separate strips laid side by side and then served with a coating of tape to hold them together, is preferable. It has the advantage of partially eliminating eddy-currents in the conductors themselves.

For armatures having outputs exceeding 200 amperes bar-armatures are preferred, owing to the inflexible nature of wires that are thick enough to carry these currents. The two classes comprise several varieties as under:—

WIRE-WOUND ARMATURES.	BAR-ARMATURES.
Single round wire.	Round bars.
Two or more round wires in parallel.	Rectangular bars.
Stranded wire.	Imbricated rectangular strips.
Single square wire.	Rectangular bars of compressed stranded wire.
Single rectangular wire.	Special forgings.
Laminated strip conductor.	

For bar-armatures, rectangular bars set edgeways to the core are more frequent than round bars; but armatures in which solid bars are set on the outside of a smooth core are liable to a serious waste of work that does not occur with wire-wound armatures. When the conductors present a considerable breadth, eddy-currents are set up in them as they enter or leave the magnetic field, owing to the fact that one edge of the bar may be passing through a field the density of which is very different from that of the field through which the other edge of the same bar is passing. Assuming a peripheral speed of 1700 to 1800 feet per second, it is found in practice impossible by any shaping of the pole corners to avoid excessive heating of solid copper bars on the armature if their breadth exceeds 5 mm. The work wasted in producing these eddy-currents may even reduce the efficiency of the dynamo by more than 5 per cent. This does not, however, occur in those armatures in which the bars are sunk deeply between teeth, or pass through holes in the core-disks. To reduce such losses, bars made of several strips oxidised on the surface, or lightly insulated by oiling or enamelling, and united only at their ends, have been used. Crompton[1] has proposed several modes of twisting or imbricating around one another two or more strips, so as more effectually to neutralize the eddy-currents. More recently he and other makers have used bars made of stranded copper wire compressed into a rectangular form, each wire being oxidized or lightly insulated.

Yet another mode of armature construction, described later, consists in winding the insulated wires or strips upon special formers or moulds, in groups which are afterwards laid on or around the armature core. One advantage in such methods is the greater ease of securing perfect insulation between those parts of the windings which differ greatly from one another in potential. In drum-windings, if the conductors lie in one layer, there is an extreme difference of potential between each conductor and its next neighbour.

[1] See *Journal Institution Electrical Engineers*, xix. 240, 1890.

Whereas if they lie in two layers, an intermediate sheet of insulating material can be laid between. A two-layer winding is extremely convenient in drum-armatures, as it facilitates connexions.

Wire-wound armatures are usually well served with shellac varnish or indiarubber solution after the winding is completed. They should be well dried in a stove at steam-heat after varnishing.

Modes of Winding Ring-Cores.—When a smooth ring-core is to be wound it is frequent to stencil upon the end faces a number of radial lines corresponding in breadth to the

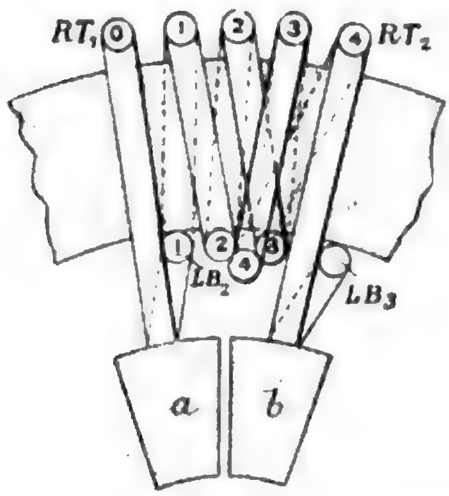


FIG. 226.—WINDING DIAGRAM. RING-ARMATURE.

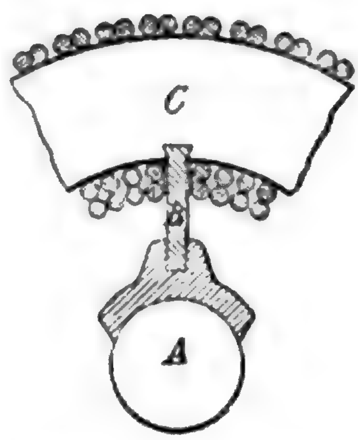


FIG. 227.—CROMPTON'S WIRE-WOUND ARMATURE.

separate sections, so as to guide the winder in his work. With toothed cores no such plan is needed.

Ring-winding is, in general, easy; nevertheless care must be exercised. The separate "sections" of the coil are almost invariably wound on the cores separately, leaving the ends projecting, secured temporarily with string, and these ends are subsequently connected together and to the commutator. An inexperienced workman may easily connect up wrongly; making a left-handed winding instead of a right-handed one or *vice versâ*. Hence it is well to provide him with some such working drawing as Fig. 226, which relates to a right-handed winding having four turns in each section. The wire marked "0" is the last or outer end of the section previous to that considered. This end will eventually be brought down to a

bar *a* of the commutator, and from this bar will go out the beginning or left-bottom end, marked L B, of the section in question. Looking at this diagram the winder will see that the wire L B must pass under the core to the far end and then return over the top, thus making turn No. 1. It will then bend down to the right, be threaded through again, and make turn No. 2; again, and make turn No. 3; but as the inner space is narrower than the outer space, turn No. 4 will probably have to ride on, or partly bed between, the turns already wound. The right-top end, marked R T, will eventually be joined to bar *b* of the commutator. If the winder is shown that the right-top wire of one section joins the left-bottom turn of the next section at the commutator, he will have no excuse for mistakes. One way of arranging the windings on a ring, with two layers internally and one externally, is shown in Fig. 227. The winding of multipolar rings is sufficiently considered in the previous chapter.

For arc-lighting armatures, and in general those which have numerous convolutions of wire to each section, it is convenient to prepare the wire in separate lengths sufficient for each section, and to coil each length on small shuttles, each length being wound upon *two* shuttles, which are alternately used for successive layers. By this device both ends of the wire that constitutes a section are brought to the outside instead of one of them leading directly down to the bottom layer, as in ordinary bobbin winding.

For those machines that only require one, or two, complete turns to each section, it is common to have the copper conductors prepared beforehand upon separate formers, and ready taped to be slipped on over the cores. Crompton introduced the forms illustrated in Fig. 228, consisting of drawn copper of nearly rectangular section twisted at the ends so as to pack closely in the interior of the ring. These conductors are sprung on over the ring-core, and afterwards coupled up so as to make a continuous winding.

In the large multipolar ring dynamos with internal field-magnet and external commutator, now so much used for central stations in Germany, the windings are so constructed that

their outer part serves also as commutator, as in Plate VIII The armature consists of core-rings built up of segmental plates, shown in section at *b*, Fig. 229, supported by driving-rods *a* which pass through them. After being covered with suitable insulation, the copper conductors *c d* are slipped on over them and coupled up to make a continuous spiral winding. The insulation between is usually a preparation of paper. The

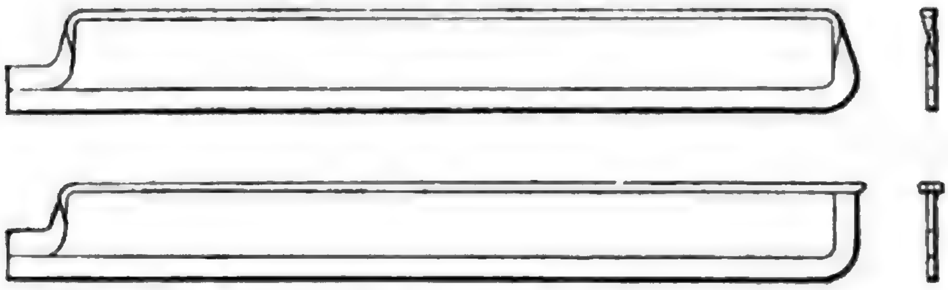


FIG. 228.—WINDINGS OF CROMPTON'S ARMATURES (1886).

outer part *d* of the copper conductor is made both deep and broad, and serves as a commutator bar. The brushes (not shown) are fixed upon the projecting bar *e*, and trail on the outer periphery of the copper windings of the ring. At *f* is a lever for raising the brushes out of contact.

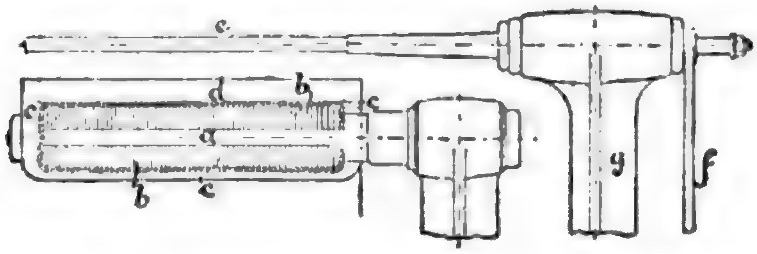


FIG. 229.—CONSTRUCTION OF GERMAN MULTIPOLAR RING-ARMATURE.

Drum-Winding.—Drum-armatures of all types may all be regarded as modifications of Siemens' well-known longitudinal shuttle-form armature of 1856, a multiplicity of sections of the coils being employed to afford continuity in the currents. The drum pattern was invented in 1872 by von Hefner Alteneck, of the firm of Siemens and Halske, of Berlin. In this system, as in the Gramme ring, the successive "sections" or groups of coils that are wound on the core, are connected together continuously, the end of one section and the

beginning of the next being both united to one segment of the commutator. It is important to note a difference between drum and ring-winding. In a ring-winding the volts induced in any one section (at a given speed) depend only on the magnetic field at one side of the armature; but in a drum-winding the volts induced in any one section depend on the two magnetic fields at the two sides, since each winding wraps over the drum nearly diametrically. As a result, drum-wound armatures are less liable to spark, and they suffer less than ring-wound armatures from inductive reactions.

The advantages of the drum form of armature appear to be (1) that they require less wire than the ring-armature of equal size; (2) are free from liability to false inductions (p. 68), and therefore more independent of the form of the pole-pieces; (3) have smaller cross-magnetizing tendency than ring-armatures. Their disadvantages hitherto have been: (1) greater difficulty of construction; (2) greater difficulty of securing proper insulation on account of over-wrapping of end conductors; (3) greater difficulty of ventilation; (4) greater difficulty of executing repairs.

Siemens' Winding.—In some of the earlier patterns of Siemens' machines the cores of the drum were of wood, over-spun with iron wire circumferentially before receiving the longitudinal windings. In another of their machines there was a stationary iron core, outside which the hollow drum revolved; in other machines, again, there was no iron in the armature beyond the driving-spindle. The process of constructing the armature employed down to the year 1885 is illustrated in Fig. 230; there being two layers of coils all over the drum. Although, for the sake of rendering the connexions more intelligible, the commutator is shown in Fig. 230 in its place on the axle, it is not, as a matter of fact, put into its place until after all the sections have been wound, the ends of the wires being temporarily twisted together until all can be soldered to the connecting strips of copper.

So far all is simple, but when we pass on to the construction of bar-armatures, new complications arise.

To connect the conductors of a bar-armature across the

ends of a drum is not so simple a matter as might at first appear. Suppose that a scheme of connexions has all been worked out beforehand, and that a winding-table has been

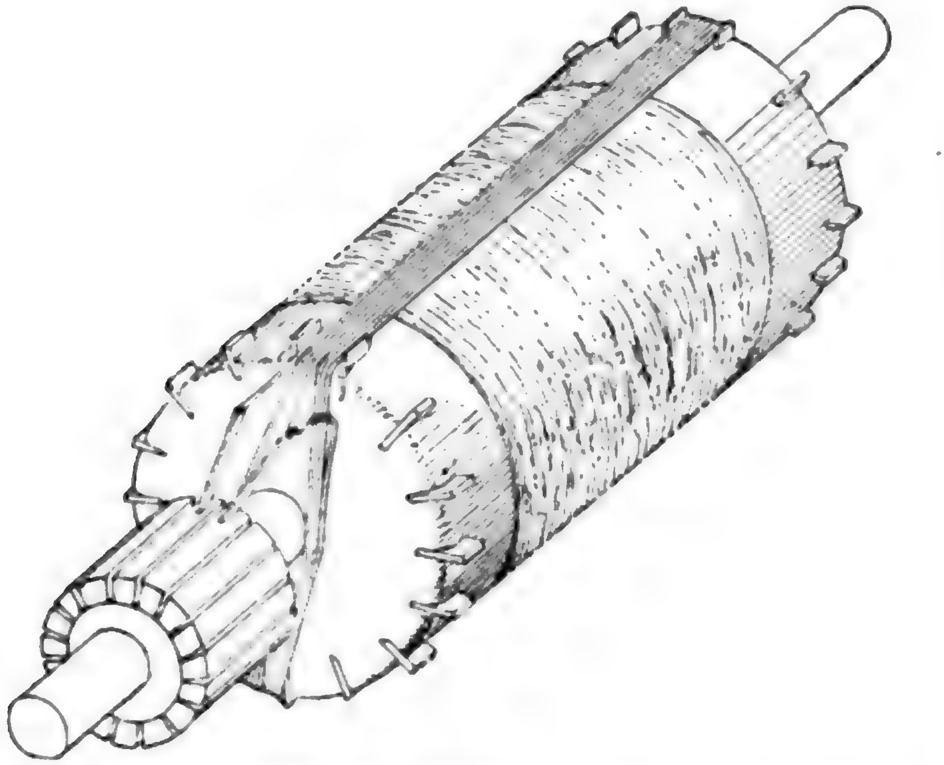


Fig. 230.—Method of Winding Siemens' Armature.

prepared in which the order of the end-connexions is set down. It yet remains to determine the mechanical devices for the end-connectors which shall be compatible with working conditions. The end-connectors must be good conductors, sufficiently well insulated from one another, allowing of repairs and ventilation, and mechanically sound. Wire-wound drums often present an ugly over-wrapping at the ends, which stops ventilation and hinders repairs. Quite early, Messrs. Siemens devised, for their electroplating machines, a system of uniting by spiral connectors (Fig. 231) the ends of the copper bars. To connect any bar with that lying next to the one diametrically opposite, two evolute

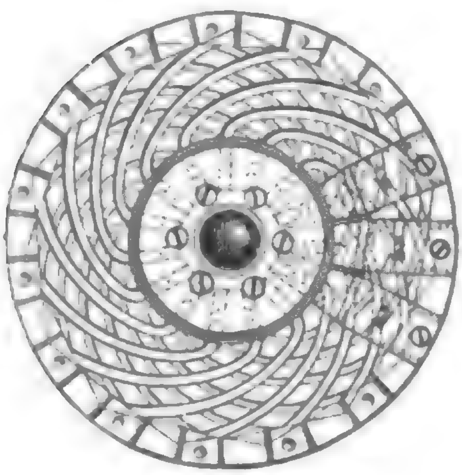


Fig. 231.—Siemens' Bar-Armature.

spiral strips of copper were applied, one bending inwardly, the other outwardly, their junction being mechanically secured to a block of wood on the shaft. Their outer ends were attached to the bars by silver solder. At each end of the drum these spiral connectors constituted two separate layers. These systems of evolute spirals, with more or less modification, are to be found in the majority of recent drum-armatures. A common form of conductor cut from sheet copper is illustrated in Fig. 232; a second form is made of strip folded.

Edison's modification of the drum-armature was alluded to on p. 260. It was manufactured under a royalty from the

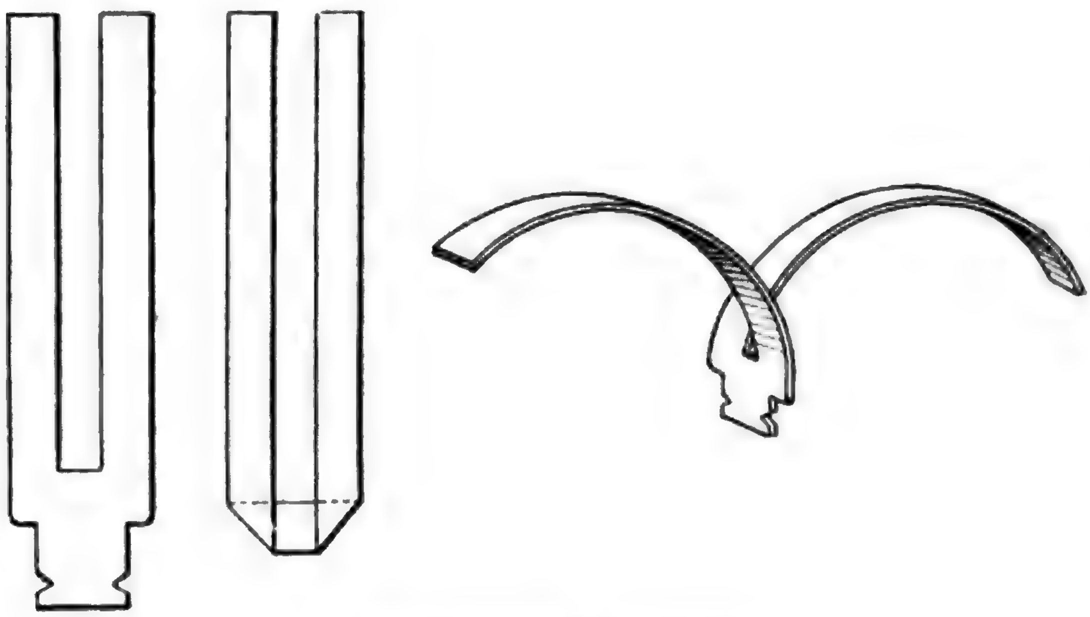


FIG. 232.—EVOLUTE CONNECTORS.

Siemens patents until the expiry of the latter. In Edison's larger dynamos of the years 1883 to 1885, the armature was constructed of solid bars of copper, arranged around the periphery of a core consisting of thin iron disks separated by mica or paper. Fig. 233 shows the armature removed from the machine. The ends of the bars are connected across by washers or disks of copper, insulated from each other, and having projecting lugs, to which the copper bars are attached. The construction was mechanically excellent, but it did not admit of ventilation; and the stray field at the ends of the armature set up eddy-currents in the substance of the copper disks. It was abandoned in favour of better methods.

In the Hopkinson armatures built by Mather and Platt, a return was made to a system of evolute connectors. The construction, as carried out for a machine in which there is one convolution in each section of the winding, is indicated in Fig. 234.

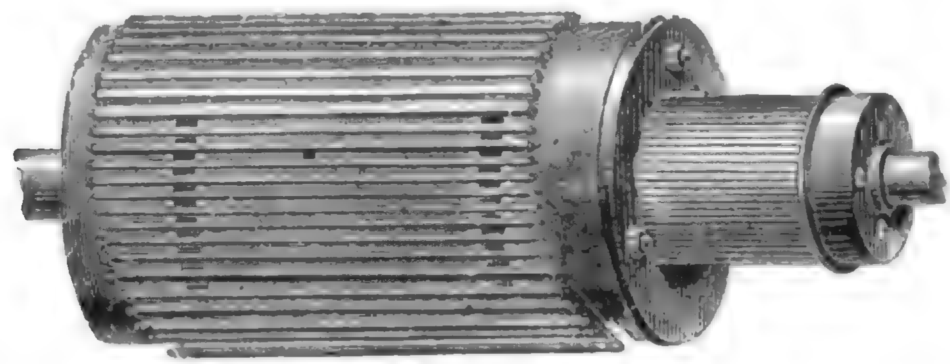


FIG. 233.—ARMATURE OF EDISON DYNAMO.

The core, which is built against a shoulder on the shaft, consists of numerous disks of thin iron, but with a few thicker core-disks *d, d,* interposed at the ends and at intervals between. These are clamped up by nuts at the end near the commutator C. The conductors of copper are provided with driving lugs

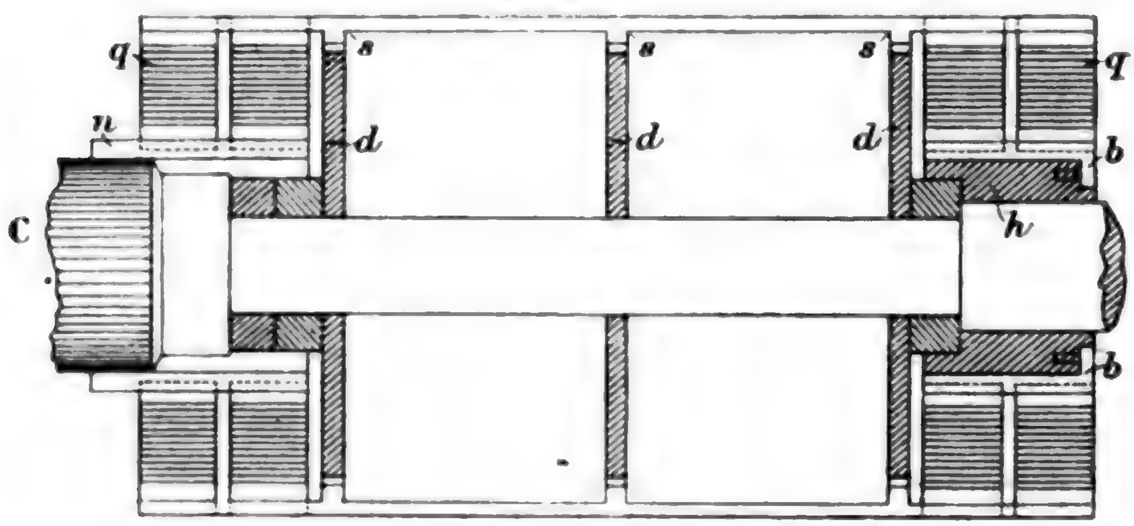


FIG. 234.—SECTION OF HOPKINSON'S DRUM-ARMATURE.

s, s, which, properly insulated, project into notches cut in the thick core disk. The systems of spiral connectors are shown in section at *q q*. At the commutator end they join the conductors down to a set of copper pieces *n*, which run to the corresponding bars of the commutator. At the other end

the spirals are inserted into a set of copper pieces *b* assembled around a wooden hub *h* by which they are driven, being screwed in through end lugs. For armatures in which each section consists of two convolutions, it is necessary to provide four layers of spiral connectors at each end.

Many successive modes of drum connexion have been tried by Mr. Crompton. In conjunction with Mr. Swinburne he devised a method of connecting the conductors of a drum-armature which enables the core to be ventilated. The fundamental point in this construction was illustrated in the former edition of this work, and consisted in the use of cranked ends to the bars, together with spiral evolute connectors to join across diameters at the ends. The same method of connecting was applied to Swinburne's plan of chord winding (p. 246).

The difficulty of getting at the inner spirals when they are disposed in two layers led to another suggestion by Crompton and Kyle, namely, turn the spiral connectors outward instead of inward, at the ends of the drum, which thus becomes enlarged in diameter.

The recent modes used by Crompton for drum-armatures are sketched in Figs. 235 and 236.

In the first of these, which is for a 2-pole dynamo, the spiral connectors, stamped out of sheet copper, are driven by mechanical attachment to a clamping sleeve keyed to the shaft. In the second, which is for a 4-pole machine, the spiral connectors, being shorter, do not require to be similarly tongued. The conductors or armature bars are made of stranded wire compressed to rectangular section.

A recent armature built by the Oerlikon Company is shown in Fig. 237. It belongs to the 60-kilowatt machine described on p. 415, and is a good example of a 4-pole drum with evolute connectors. The core-disks have straight teeth between which the conductors lie in pairs side by side.

A method based on that of Paris and Scott is used by Kapp both for bipolar and multipolar drums. The connectors are stamped out from thin sheet copper in the form of semi-circular or quadrantal arcs, provided with lugs (as shown on

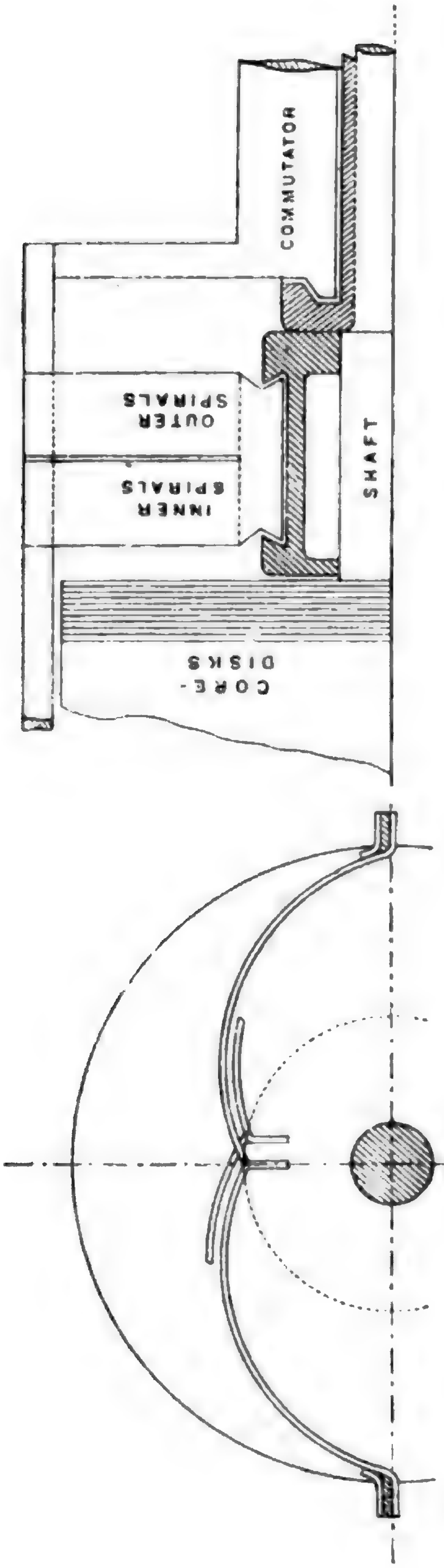


FIG. 235.—CROMPTON DRUM-WINDING FOR CENTRAL STATION MACHINE, 2-POLE DYNAMO.

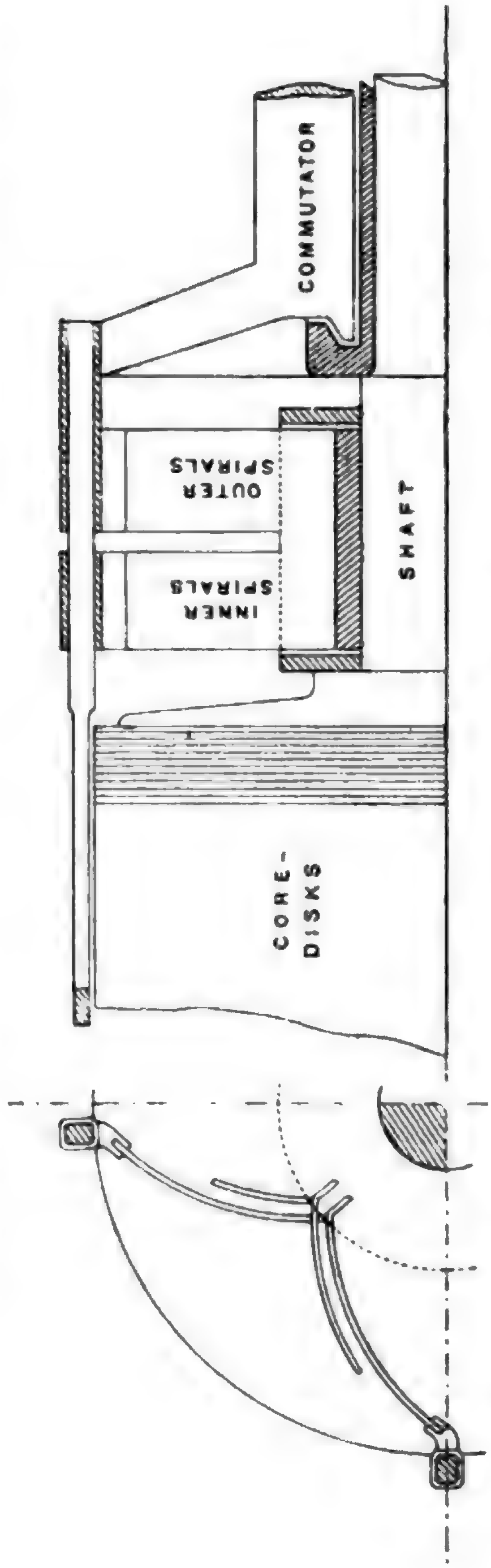


FIG. 236.—CROMPTON DRUM-WINDING FOR LARGE OUTPUT 4-POLE DYNAMO (PARALLEL CONNEXIONS), 4 SETS OF BRUSHES.

Plate II. Fig. 2) which can be bent, one forward, one backward, thus enabling connexions to be made by a whole series of such connectors arranged skew-wise, with suitable insulation between, in a carriage or bobbin mounted on the shaft. The connectors are assembled together to the proper number, and held in with binding wires in the channel of this carriage, which is then put in place, and the lugs are soldered into grooves cut in the ends of the armature conductors, which for this purpose are made alternately long and short at their ends. The best way to understand this method is to make a few

FIG. 237.—4-POLE DRUM-ARMATURE OF OERLIKON CO.

FIG. 238.—SEPARATE SECTION OF EICKEMEYER'S ARMATURE.

model connectors in paper or cardboard, and lay them over one another.

Eickemeyer's methods of construction, which have been largely used in the States, and also in England by Mr. Parker, are distinctive in that the individual "sections" of the winding, whether consisting of one single turn, or of a large number of turns of small wire, is first shaped upon a separate former, and each such section is separately insulated. Afterwards the sections are assembled in their places upon the core of the drum. Fig. 238 shows one of the forms given to the sections. The lower part will form part of an inner layer, and the upper part, which is longer, will form part of an outer layer in the assembled windings. The completed armature, with its binding wires, is shown in Fig. 239.

FIG. 239.—EICKEMEYER'S ARMATURE, COMPLETE.

The cylindrical pattern of drum-armature adopted by Brown is shown in Fig. 240, and in detail in Plate VII.

The conductors (in holes through the core disks) lie in two layers, and the end-connexions are made without evolutes or any other parts that would cover up the end-faces of the drum. The conductors being extended and bent, the outer layer to left, the inner to right, thus continue the cylindrical surface, which projects at both ends beyond the core. It has the advantages of good ventilation and accessibility. In Plate VII. it will be seen that these projecting cylindrical ends are supported by an internal flange attached to the stout end core-plates. This mode of connexion has been used by Brown since the beginning of 1892 for drums, and is also adopted for sunk windings in alternate-current generators and in the

rotating parts of all alternate-current motors, both single and polyphase, that have windings upon them. It has since been adopted by both the Westinghouse Co. and by the General Electric Co. The Allgemeine Co., of Berlin, uses a somewhat

FIG. 240.—CYLINDRICAL WOUND DRUM-ARMATURE (4-POLE) (BROWN).

similar plan of end-connexions, but the sunk conductors lie in one layer only. A very similar mode of winding was patented by Hon. C. A. Parsons. But the arrangement with one layer is less convenient as it requires that alternate conductors should bend under the others, since there must be two layers of connecting-pieces sloping in opposite ways.

CHAPTER XIV.

COMMUTATORS, BRUSHES AND BRUSH-HOLDERS.

DYNAMOS for furnishing continuous currents require a *commutator* (sometimes called a *collector*) and *brushes* to collect the current. The essential action of these organs has been already described (see pp. 78 and 80); and the causes that give rise to sparks are discussed in Chapter IV., p. 81, and in Chapter XVI. We have now to consider the design and construction of these organs.

We may distinguish three types of apparatus for collecting the currents from dynamo machines.

I. Continuous-current dynamos with closed coil armatures as used for incandescent lighting and other work requiring a constant or nearly constant potential, are furnished with a commutator of the Pacinotti type, that is to say, consisting of a considerable number of parallel bars secured around an insulating hub, and presenting a cylindrical surface, against which press a pair (or in some cases more than one pair) of brushes or sets of brushes.

II. Continuous-current dynamos of the open coil type, as used for arc lighting, and giving a constant or nearly constant current, are provided with a commutator consisting of a comparatively small number of segments, each covering a considerable angle, and separated by air-gaps from one another. These are described in Chapter XVIII.

III. Alternators with revolving armatures need a pair of collecting rings of metal, each provided with one or more brushes, or some analogous device to form a sliding connexion with the circuit. Alternators with revolving field-magnets of which the winding also revolves, need a similar device to convey the exciting current to the moving coils. These devices are

considered at the end of the present chapter, which is in the main devoted to apparatus of the first of the three classes enumerated.

Commutator Bars.—The number of bars of the commutator depends on the scheme of winding and on the number of sections in which the armature winding is grouped. Increasing the number of bars diminishes the tendency to spark (p. 83); and lessens the fluctuations of the current (p. 178). An even number of bars is preferable to an odd number; and for ring-wound armatures the cores of which are usually carried on three-armed spiders, it is preferable that the number of bars should be a multiple of three. There are, however, two practical reasons against making the number of bars very great. Increasing the number increases the cost. Again, in large machines having but one turn of the armature winding from each bar of the armature to the next, the number cannot be greatly increased without exceeding the voltage desired. For example, in a bipolar Edison-Hopkinson machine for an output of 1100 amperes at 105 volts, only 43 convolutions are required. On the other hand, it is found for small dynamos, that if the number of bars is increased, each bar becomes so thin that a brush of the proper thickness to collect the current would bridge more than two commutator bars at once. Again, the bars should be of a length proportioned to the number of amperes that is to be taken off at them. Modern practice varies somewhat, but it may be fairly represented by some such figure as 1·2 inches for every 100 amperes. The mode of attachment of the bars should be such as to make the greatest amount of length available. They should also be of considerable radial depth, to allow for wear, as the commutator needs to be turned down from time to time to preserve cylindricity. As for the material, most makers use hard-drawn copper, made in long lengths of the proper section, and cut off to the length required. Some American makers use drop-forgings of copper, stamped to shape with projections for clamping and connecting to the windings. Commutators to be used with carbon brushes need to be made from 1½ to 2 times as large as they need be

if copper brushes are used, for the carbon brushes require to touch over a larger amount of surface (for the same current), but ought not, except in the special cases of duplex and triplex armatures (p. 272), to touch more than two commutator segments at one time.

Insulation.—It is needful to have a good insulation between each bar and its neighbours, and a specially good insulation between the bars and the sleeve or hub around which they are mounted, and also between the bars and the clamping devices that hold them; for the difference of

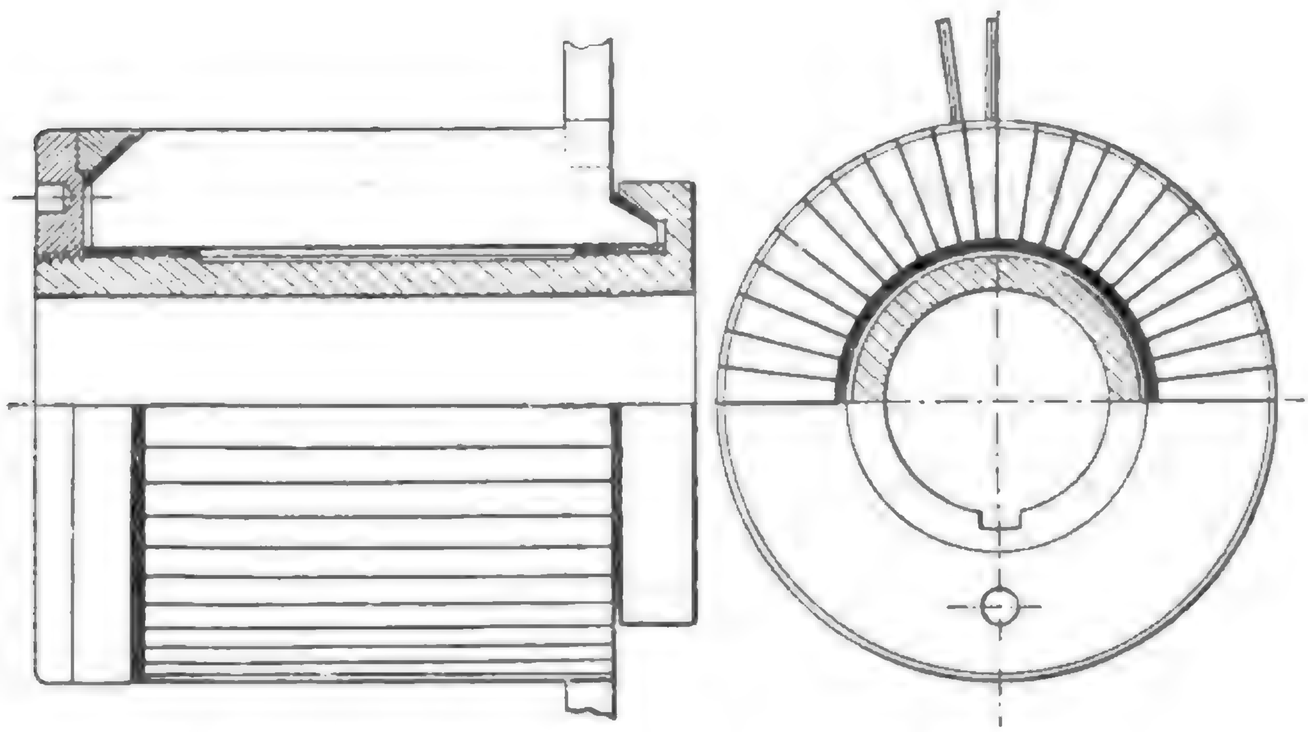


FIG. 241.—SECTION OF COMMUTATOR (PATERSON AND COOPER).

potential is small between neighbouring bars, and much larger between the bars and other metal-work. The insulating material must not absorb oil or moisture: hence asbestos and plaster are inadmissible. Vulcanized fibre and Willesden paper are not by themselves adequate, though mechanically strong, as they are both liable to absorb moisture. Mica is the one satisfactory material used by English and American makers; but in Germany a preparation of paper is frequently substituted. Washers of conical form are sometimes built up of thin pieces of mica held together by shellac and consolidated while hot under great pressure. Between

the bars mica may be used very thin with advantage. Commutators with air-gaps between the bars have been used. But with air-insulation there is some trouble in keeping the gaps from being filled by metallic dust from the wearing of the brushes.

Construction of Commutators.—In the construction shown in Fig. 241, the bars are clamped in place by fitting at one end into a groove in a gun-metal sleeve, and at the other by an external clamping ring which is forced over their bevelled ends by a large screw-washer. The insulation is carried out by thin slips of mica between the bars, and layers of mica and vulcanized fibre around the sleeve and clamping surfaces. The clamping ring in this case reduces the available surface for the brushes.

In the Gülcher Co.'s machines a construction is adopted which is illustrated by Figs. 242 and 243, and of which a section is given in Fig. 244. The drawings relate to a four-pole machine with only two sets of collecting brushes. Here also the bars of the commutator are assembled around a sleeve fixed on the shaft, but are so arranged that their whole length is available for contact with the brushes; being held in position at their ends, with insulation between the V-shaped nicks in the bars and the clamping pieces which enter them.

A very similar arrangement obtains in Kapp's dynamo (Fig. 1, Plate II.), in which the clamping nicks in the ends of the bars are made deep; the end insulation being effected by three rings of vulcanized fibre, one flat, the other two conical, which fit into the ends of the assembled bars. It is good that a sufficient length of insulating surface should exist between the bars and the metal mountings, for there is less likelihood of a fault occurring if the possible leakage-path over the surface is a long path, than if it is short.

In building commutators it is usual to assemble the bars to the proper number, with the interposed pieces of mica, clamping them temporarily around the outside with a strong iron clamp, or forcing them into an external steel ring by hydraulic pressure. They are then put into the lathe and the interior cylindrical surface is bored out. Then the ends are

FIGS. 242 and 243.—COMMUTATOR AND BRUSH-HOLDERS OF GÜLCHER CO'S 4-POLE MACHINE.

turned up, with the annular hollows to receive the clamping-pieces. The whole is then mounted, with proper insulation, upon the sleeve, and the end clamping-pieces are screwed up. It is then heated in a stove, and the end clamping-pieces are further tightened up. Lastly the temporary external clamps or rings are removed and the external surface is turned up true. The sleeve should be properly keyed or otherwise secured to the shaft, that there may be no slip between it and the armature to which it is afterwards connected. Connexion is made with the armature conductors by means of radial strips or wires of copper, which are inserted into a cut

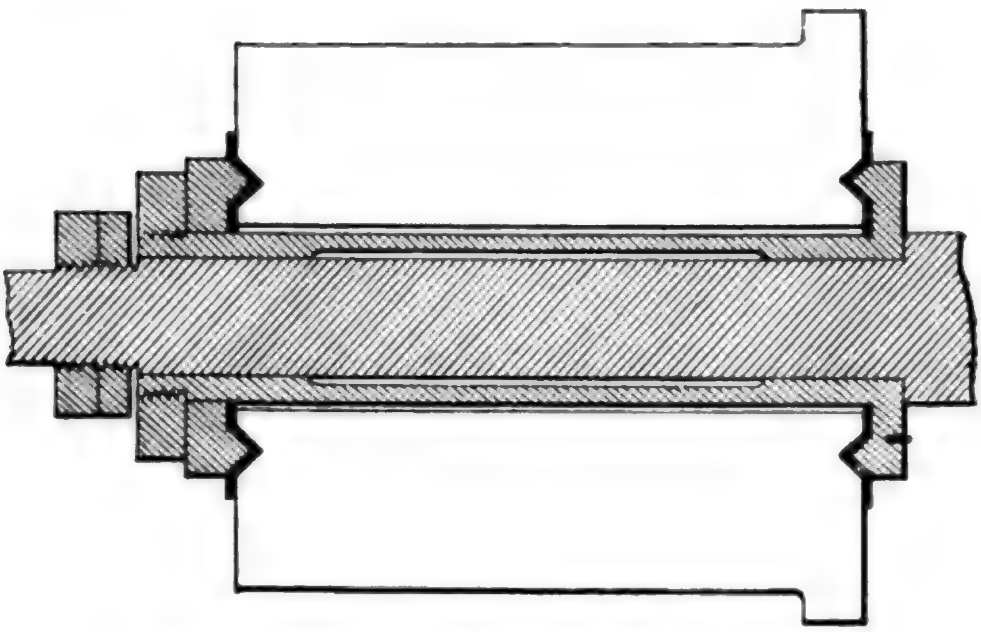


FIG. 244.—SECTION OF COMMUTATOR (GÜLCHER CO.).

sawn in the corner of each bar, and firmly held there. A good mode is to rivet the strip connectors into the corners of the bars before they are assembled, each riveted joint being also sweated in with solder. Fig. 245 shows a simple mode of doing this; while Fig. 246 shows commutator bars formed with a lug to receive the rivet *r*. In this example the nick *h* is to prevent the brushes from being set too near to the radial strips.

It is important that these connecting strips should be properly attached, since they are subjected to considerable mechanical forces. Twice in each revolution each such strip carries a strong current; and, owing to the existence of a

stray magnetic field, is consequently racked toward one side. Before this was understood it gave rise to frequent accidents.

In some large recent machines there is no separate commutator; the brushes trailing against some part of the copper conductors of the armature winding themselves. This is the case with the great Siemens dynamos at Berlin (Plate VIII., and Fig. 229, p. 302).

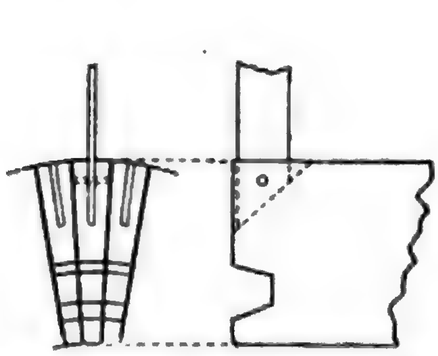


FIG. 245.—ATTACHMENT OF RADIAL CONNECTOR.

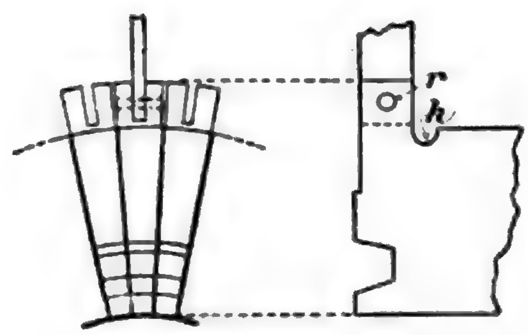


FIG. 246—ATTACHMENT OF RADIAL CONNECTOR.

Brushes.—The kind of brush most frequently used for receiving the currents from the collector, consists of woven copper wire gauze folded on itself and compressed as shown in Fig. 247, *e*. It was introduced about twelve years ago by Mr. A. P. Trotter. In order to prevent fraying at the edge it is usual to fold the gauze obliquely, as in Fig. 247, *f*. Sometimes the core of this gauze is made of exceedingly fine copper wires either straight or in soft plaited strands. The earliest sort of brush used consisted of a quantity of straight copper wires laid side by side, soldered together at one end, and held in a suitable clamp. Two layers of wires were often thus united in a single brush, as shown in Fig. 247 *a*. The object of all these devices was to secure a contact at a large number of points.

Brushes are also made of broad strips of springy copper slit for a short distance so as to touch at several points Fig. 247, *b*. Such are used in the Brush and Thomson-Houston arc-light dynamos. This kind of brush is usually set tangentially to the surface of the commutator, not sloping to it at an angle as is the case with the thicker kinds of brushes.

Edison has used as brushes a number of copper strips placed edgeways to the collector, and soldered flat against one another at the end furthest from the collector, Fig. 247 *c*. In some machines, a compound brush made up alternately of layers of wire, like Fig. 247, *a*, and slit strips of copper, like Fig. 247 *c*, has been adopted.

Other makers have used a number of very thin copper strips laid over one another as in Fig. 247 *d*, held together in a suitable clamp.

Rotating brushes in the form of metal rollers or disks have been repeatedly tried, but are not successful.

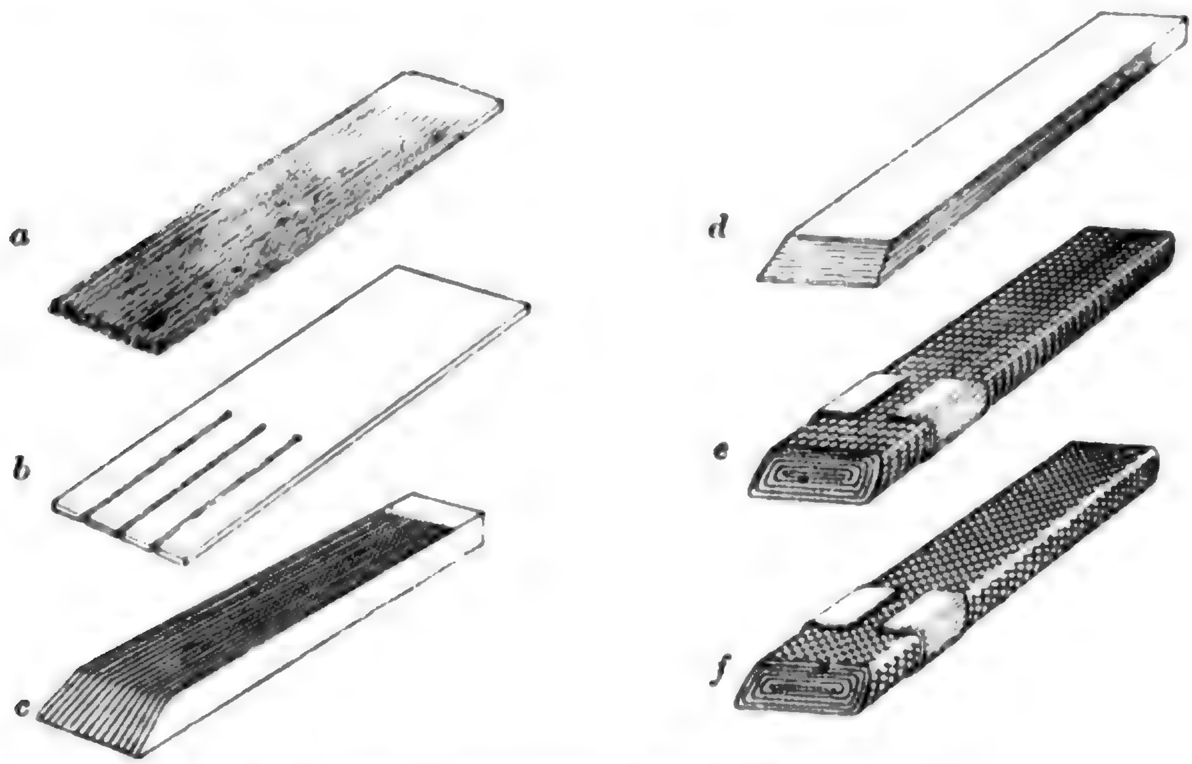


FIG. 247.—DIFFERENT KINDS OF BRUSHES.

It was suggested[1] by Professor G. Forbes to replace the brush by a slab of fine-grained and good conducting carbon. Carbon brushes are indeed used now frequently, both for dynamos and for motors. It is usual to provide a cross-section of about 1 square inch for each 50 amperes; but a really good conducting carbon will carry double this. They wear the commutator less than copper brushes, and facilitate sparkless collection: but they are more liable to heat, and need larger commutators.

[1] Specification of Patent 1288 of 1885.

It is usual, for all but the very smallest machines, to place at least two brushes side by side (as in Fig. 250, p. 323), instead of one broad brush. This allows of either brush being removed for trimming and replaced while the machine is running. It also tends to equalize the wear of the commutator, each brush being separately pressed against the surface; and the gap between two brushes can be covered by a brush at the other side. No rule can be given for the number or breadth of brushes that will apply to all cases. Some makers reckon an additional inch breadth of brush for each hundred amperes of output. Nor is it easy to give a general rule for the thickness of brushes. A thickness that will bridge the film of insulation between bar and bar is not sufficient, for each section of the winding requires to be short-circuited for a certain brief time, in order that the current in it may be reversed. The minimum thickness of brush (or breadth of its oblique end) seems to be about 1½ times the thickness of the commutator bar. There is no objection to a greater thickness in those dynamos that have a large neutral zone about the neutral point; or in which the curve of induction (Fig. 66, p. 78) has a broad flat top. But when a brush of great thickness is used another effect arises, namely, a waste in heating owing to the difference of potential between the parts of the commutator respectively in contact with the advance edge and hinder edge of the brush. To reduce this effect it has been proposed to use two thin brushes, one in front of the other, instead of a single thick one, with a certain amount of resistance between them.

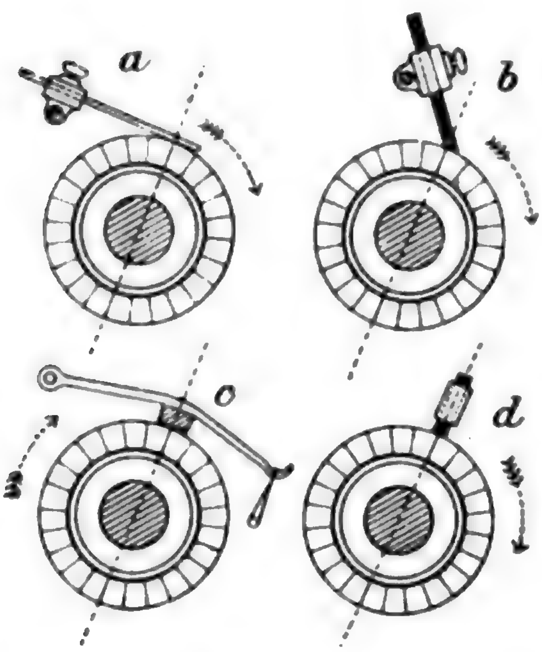


FIG. 248.—VARIOUS COLLECTING BRUSHES.

For armatures with duplex and triplex windings (p. 272) broader brushes must necessarily be used.

The angle at which brushes are set to bear upon the commutator varies with the construction. As a rule the brush is set sloping at an angle, the tip of the brush being raked in the direction of the rotation, so that it may not trip on the edges of the commutator-bars. In Fig. 248, *a*, is shown the case of a brush such as Fig. 247, *b*, set tangentially, as in arc-light machines. In Fig. 248, *b*, is a thick brush with bevelled end set at about 45°, as in most constant-voltage dynamos. Fig. 248, *c*, shows a form of brush devised by Holroyd Smith for use in motors, permitting of reversal of

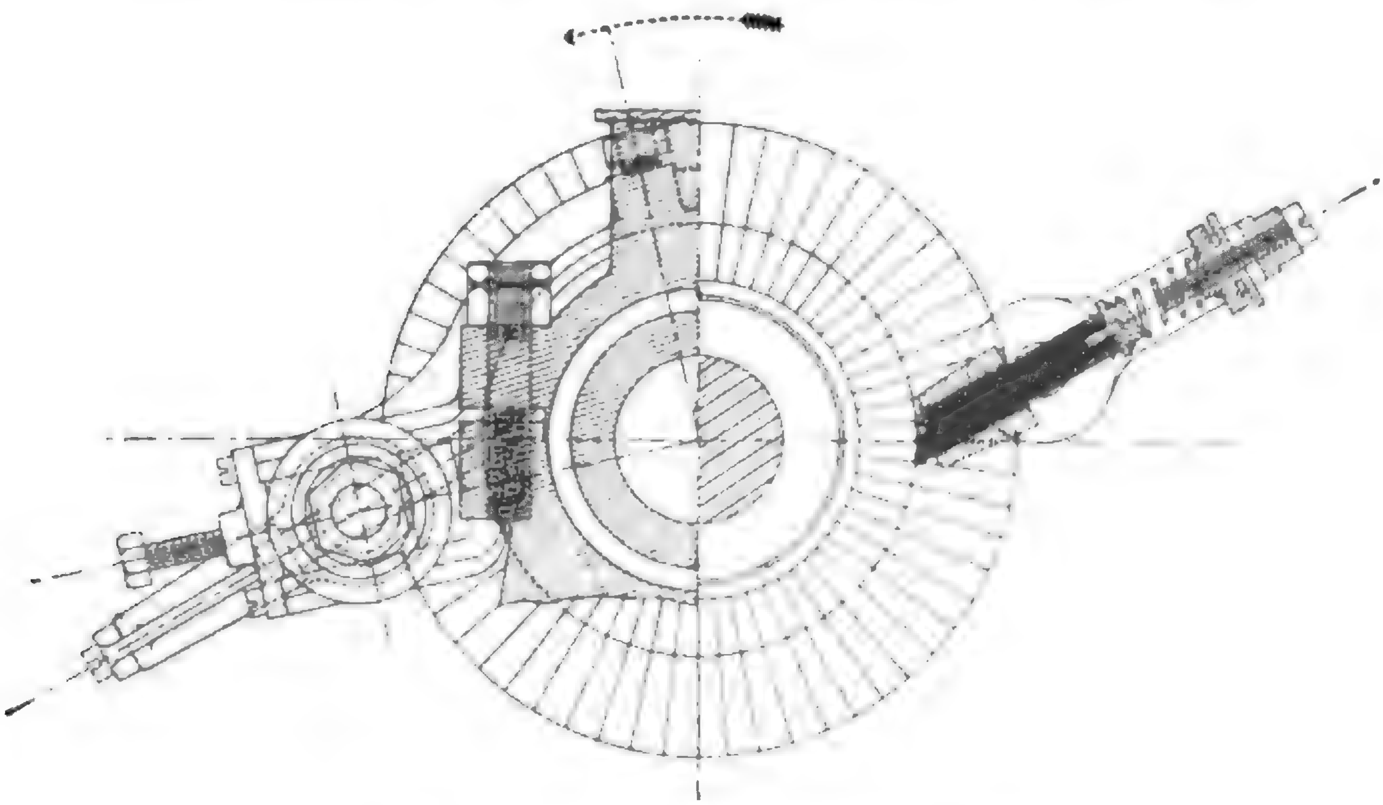


FIG. 249.—CARBON BRUSH-HOLDER (SNELL).

direction. Blocks of copper or gun-metal are attached to levers furnished with rubber bands to afford contact-pressure. In Fig. 248, *d*, is shown a carbon brush also adapted for use in reversing motors ; the brush, a rectangular block of carbon, being pressed radially through a metal slide against the commutator.

In many cases where carbon brushes are used they are set to rake in a direction opposite to the rotation, so that the end-pressure may be greater when running. Fig. 249 illustrates a carbon brush-holder for use in mining motors.

Brush-holders and Rockers.—The mechanism for holding the brushes must fulfil the following conditions :—

(1.) The brushes must be held firmly, and joined with a good metallic contact to their circuit.

(2.) Brush-holders must permit brushes to be withdrawn or fed forward as required.

(3.) Brushes must be held to make contact at proper angle to the surface of the commutator.

(4.) Brushes must bear with proper pressure upon the commutator ; if too light, they will jump and spark ; if too heavy they will cut the commutator into ruts.

(5.) Brush-holders must permit brushes to be raised from contact.

(6.) They must also permit, by a proper mechanical catch, of the brushes being held raised out of contact.

(7.) Insulated handles should be provided for all dynamos working above 100 volts, so that the brushes may be raised and adjusted without risk of shocks.

(8.) The insulation of the brush, or of brush and brush-holder together, must be very thorough.

A characteristic example of brush-holders is afforded by those of the Gülcher Company's machine. This is a 4-pole machine (cross-connected), and therefore the two brushes must make contact at two points 90° apart. A kindred example, designed by Mr. Mountain for the "Tyne" dynamo, is given in Fig. 250, which also shows the construction of the commutator and the rocker. The rocker R consists of an iron ring in two parts, which is clamped together by bolts upon a raised rim on the bearing. To this rocker are attached a handle H for shifting it so as to bring the brushes to the neutral point, and a couple of projecting lugs L (one only shown) to carry the brush-holder rods M. The latter are mechanically secured to the rocker lugs by screw nuts which hold them tightly ; but they are electrically kept from making contact with the rocker by the interposition of an insulating bush and washers of ebonite. Upon the rods M are placed the brush-holders A which can turn hinge-wise upon them. Between the hinges of A is fixed, by a screw F, a middle piece D with a

projecting tail. The brush B passes through a slot in A, being clamped by a screw C. The current is brought to the brush-holders by flexible conductors, which are soldered into sockets

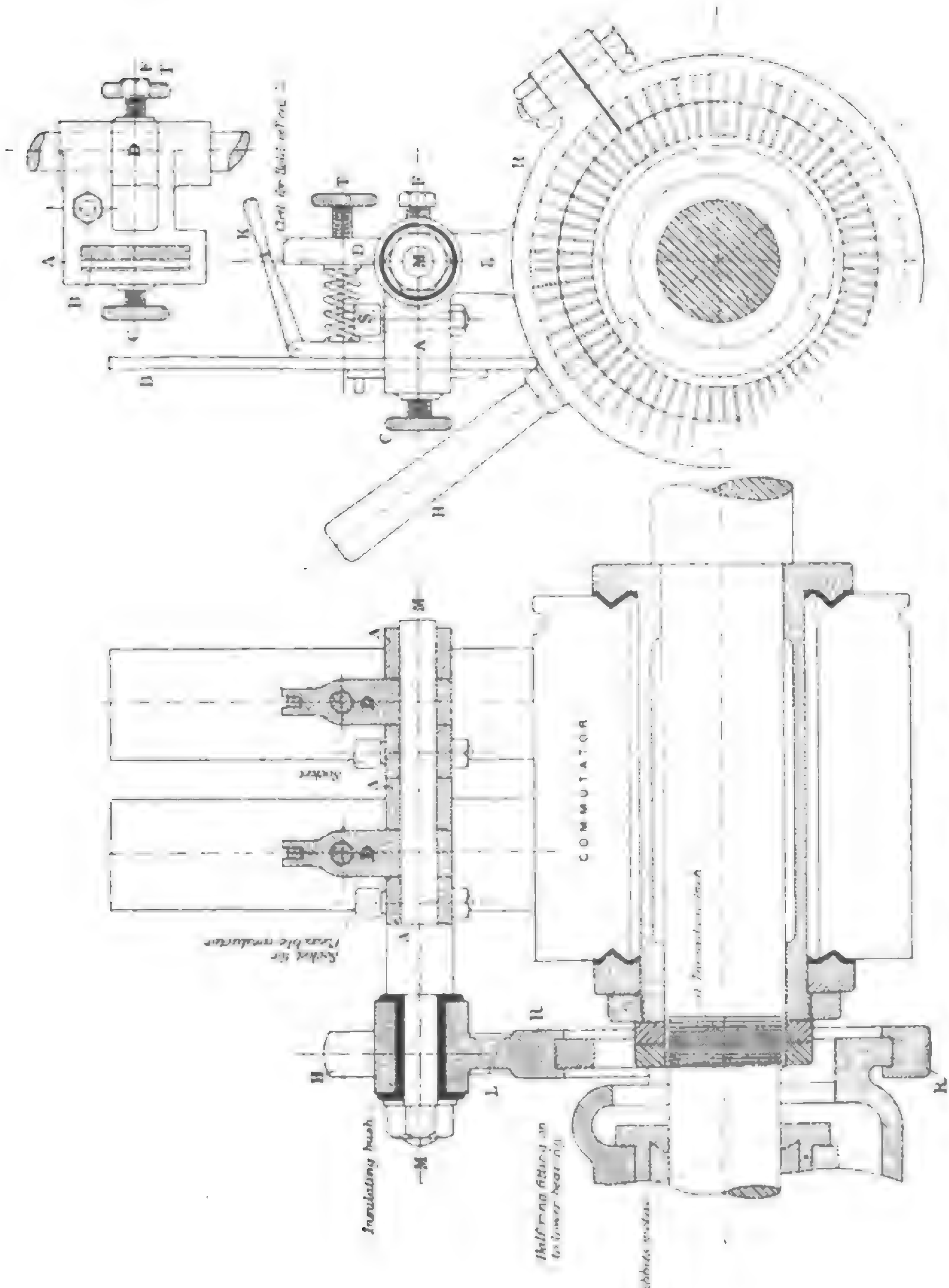


FIG. 250.—ROCKER AND BRUSH-HOLDERS OF "TYNE" DYNAMO.

provided for the purpose. The brush is pressed forward by a compressed spiral spring, the force of which can be regulated by a screw through the projecting tail of D; whilst it can be held off by means of the catch K, which can be pulled back and slipped into a cleft on the end of D. In Fig. 243, p. 316, which depicts the similar mechanism of the Gülcher dynamo, one of the hold-off catches is caught in the cleft.

The rocker and brush-holders of the Kapp 2-pole dynamo are shown in detail in Plate III. Here the mode of insulating

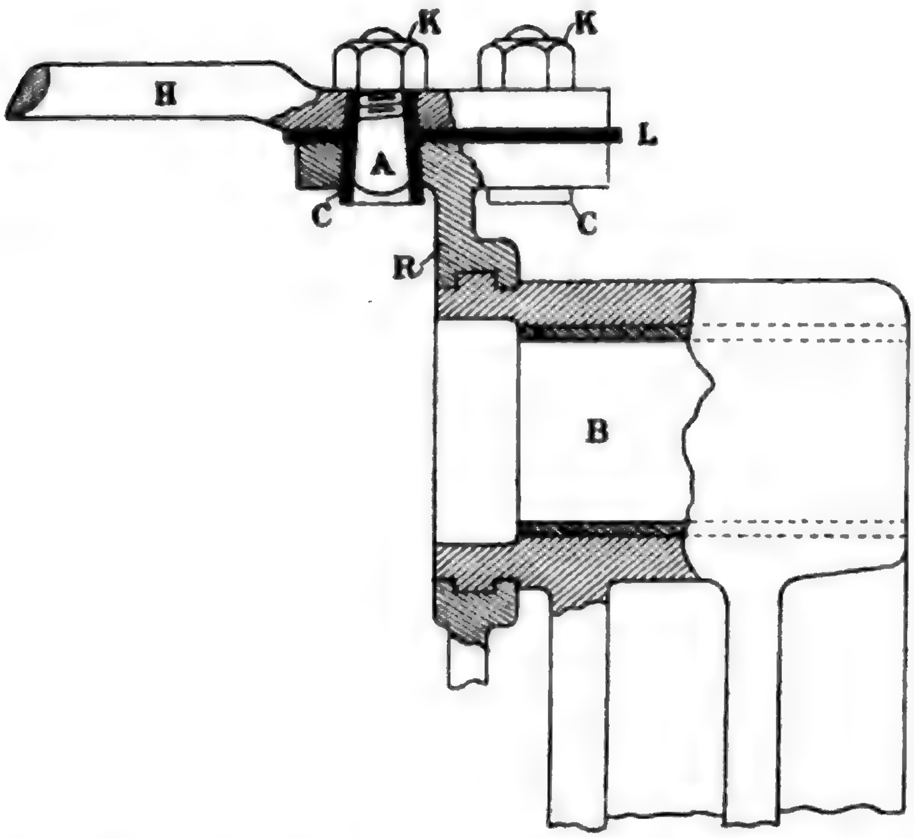


FIG. 251.—INSULATED BRUSH-HOLDER ROD (BARLEY AND STEVENSON).

is the same, but the current is led into a thick washer G; the contact-pressure is produced by an extended spiral spring stretched between a lug on the holder A and the fixed tail D; and the hold-off catch K is constituted by a straight spring which engages in a notch on the corner of A and is released by pressing up the piece Q, which is made of hard fibre. P is a pointer for setting the brushes to the right position in the holder.

A defect in the method of insulating by means of a bush

upon the brush-holder rod, is its liability to permit the rod to turn. A more solid construction is that of Fig. 251, in which the flattened end of the holder-rod H is clamped to an expansion of the rocker R by means of two conical bolts A; insulation being secured by an interposed layer L, and two conical bushes C of ebonite or fibre.

An excellent form of brush-holder, which permits the brushes to be fed forward longitudinally by a screw motion as required, has been devised by Messrs. Goolden & Co., and has a cam-motion for holding off.

Various inventors have tried to simplify the construction;

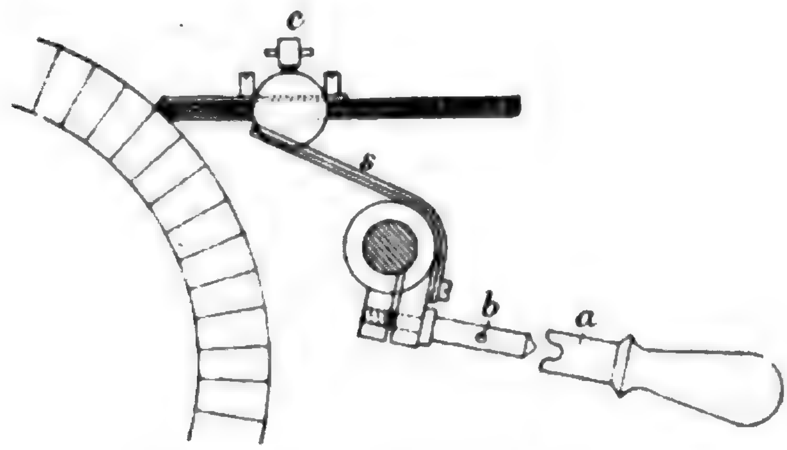


FIG. 252.—SIEMENS AND HALSKE'S BRUSH-HOLDER.

amongst them, Parsons has proposed to substitute weights for springs to give the requisite pressure.

A very simple and effective form of brush-holder, introduced by Siemens and Halske, is used largely in Germany. In this form, Fig. 252, the clamp which holds the brush is set on the end of a curved support made of several thicknesses of springy sheet brass. This is simply clamped to the holder-rod by a clamp screw which admits of the holder being shifted along the rod, or of being turned to give greater or less pressure. The tool is used for any of the required adjustments. These brushes are used with the large multipolar dynamos, such as that figured in Plate VIII., in which the second figure shows the star-shaped rocker which carries the brush-holders.

Brushes and Collectors for Alternators.

Alternators have no commutator, but they usually need a pair of sliding contacts to convey the currents to and from the rotating part. The usual device is a pair of contact rings of copper or gun-metal mounted on insulating hubs on the shaft, with one or more brushes to press on each contact-ring. In those alternators in which the revolving part is the armature, great care must be taken to insulate well the two rings from each other, and from the shaft. A deep projecting rim of ebonite should be provided between the two rings if they are situated on the same side of the machine, as in the Westinghouse alternator, Fig. 377, or the Hopkinson alternator, Fig. 411. In some alternators, the contact rings are on opposite sides of the armature, so that not only is high insulation easy, but the risk of accidental shock is lessened. Two brushes are usually applied to each ring, so as to admit of replacement while running.

In those alternators in which the revolving part is the field-magnet, contact rings and brushes are needed to bring in the exciting current. But, as the current is small and at low voltage, the collecting arrangements are simple and need no special care in insulation. In the slow-speed 3-phase alternators designed by Brown, Fig. 421, the exciting current is conveyed in through two belts of flexible stranded wire running over gun-metal pulleys.

CHAPTER XV.

MECHANICAL POINTS IN DESIGN AND CONSTRUCTION.

IN Chapter XIII. are considered the mechanical modes of transmitting the power from the shaft to the armature conductors and *vice versâ*. The design of dynamo shafts, journals, bearings, pedestals and pulleys is a matter equally requiring a knowledge of mechanical principles and practice. Such standard works as Unwin's *Machine Design* should be followed. Nevertheless there are some points in which the ordinary engineering rules cease to be entirely applicable; and it is because of this circumstance that it seems desirable to give the information embodied in the present chapter.

Pressure on Bearings.—In addition to the ordinary pressures on bearings, due to weight of the shaft and its attachments, and to the lateral drag of the driving-belt, there is in dynamo-machines a third cause producing pressure, namely the actual magnetic pull which the field-magnets exert on the armature core. This is notably great in the case of dynamos having a single magnetic circuit. An example in which the field-magnet tends to lift the armature is afforded by those machines, such as the Edison-Hopkinson, Fig. 287, p. 422, in which the magnet stands over the armature; whilst contrary examples are furnished by machines in which the armature is above the field-magnets, as in the Kapp dynamo, Plate I. and Fig. 259. If the armature is perfectly centred there will always be a tendency to drag it in such a way as to make the entire magnetic circuit more compact. This can be partially obviated by placing it eccentrically, slightly below the centre of the bored polar faces in machines of the under-type, and slightly above the centre in the over-type. In Kapp's machine the downward

pull is partly compensated by leaving the pole-tips wider apart below the armature than they are above it; or by using cast-iron pole-tips below and wrought-iron pole-tips above. This magnetic pull may amount to as much as four or five times the weight of the armature.

Gyrostatic Action of Armature.—Another point, which arises only in the case of dynamos used on shipboard and of motors running round a curve on a track, is the gyrostatic action of the revolving armature, which tends always to keep its axis pointing in the same direction. Lord Kelvin has given[1] the following formula for the gyrostatic force on a bearing.

$$F = W k^2 \Omega \omega \div g l;$$

where F is the force; W weight of armature; l length between bearings; g the acceleration of gravity; ω the angular velocity of the armature, in radians per second; Ω the maximum angular velocity of roll of ship, also in radians per second; k the radius of gyration of the armature.

Example:—In a ship rolling 20°, with a periodic time of 16 seconds a Siemens alternate-current machine (Fig. 409) running at 1300 revolutions per minute; $W = 148$ lbs.; $k = 0{\cdot}7$ foot; $l = 1{\cdot}4$ foot; and $g = 32$ feet per sec. Here $\Omega = 2\pi \times \frac{20}{360} \times 2\pi \div 16 = 0{\cdot}137$; and $\omega = 2\pi \times 1300 \div 60 = 136$. Then $F = 30{\cdot}6$ lbs. on each bearing, alternately acting up and down at each roll, if the axis o the dynamo lies athwart the ship.

It is evident from these considerations that it would be inexpedient on shipboard to employ dynamos having armatures which resemble fly-wheels in form, if the pressure due to the weight of the armature were not relatively much greater. Drum-armatures of length greater than their diameter are preferable for ship-lighting.

Journals.—From what has been said it will be clear that caution must be used in applying the ordinary rules of

[1] See Jamieson on Electric Lighting for Steamships, *Proc. Inst. Civil Engineers*, lxxxix., Nov. 11, 1884.

machine design. It is usually assumed that journals are made larger for higher speeds, because of the necessity of getting rid, by the greater cooling surface, of the heat generated at the higher speed. But it is known that this assumption leads to the rule

$$l = \mathrm{F}\, n \div \beta\,;$$

where l is length in inches; F the force (in lbs.) on the bearing; n the number of revolutions per minute; and β a constant which, according to various authorities, may vary between 66,000 and 1,000,000. With such a variation, the rule is almost useless as a guide to design; moreover it takes no account of the diameter of the journal. In all good engineering practice the ratio between the diameter and length of a journal bears a relation to the speed. For slow speeds, such as 100 revolutions per minute, the length need be no greater than one diameter; whereas for speeds of 1000 and upwards the length is five or six diameters, and in high-speed fans sometimes as much as eight diameters.

From this we get the approximate rule:—

$$l / d = 1 + 0{\cdot}004\, n.$$

The rule given above, which is an ordinary one for mill-shafting, is known not to apply to crank-shaft bearings, where centrifugal force is of little importance, but where there come heavy alternately-directed thrusts and wrenches. Still less can it strictly apply to dynamo machines. In these, for the most part, the power is transmitted through a few inches of shaft from a pulley to the armature. The journal between these two parts, if the pulley is outside, is obviously sustaining a much severer wrench than the journal at the other end; it is in many dynamos made larger and longer than that at the commutator end.

In the table on the next page are given data of sundry machines.

The safe diameter for a journal to give requisite strength depends on the load tending to bend it, as well as on the mere twisting-moment that results from the power transmitted

through it. The diameter of a shaft is usually calculated from the formula, applicable when there is no bending:—

$$d\,(\text{inches}) = c\,\sqrt[3]{\text{HP} \div \text{revolutions per minute}};$$

where $c = 2 \cdot 9$ for steel shafts.

The lateral loading of an overhung pulley, due to the belt, produces a considerable amount of bending. Taking the ratios of breadth of pulley to diameter which are usual in dynamo manufacture, it will be found that c ought to be taken as having a value variously estimated from 4·2 to 5·5.

Again, the spindle or shaft of a dynamo is subjected to bending by the weight of the armature, by the magnetic drag

TABLE OF JOURNAL SIZES.

Dynamo and Description of Armature.	Revolutions per minute.	Distance between bearings (inches).	Output (kilowatts).	Length l (inches).	Diameter d (inches).	Ratio l/d.
Edison (bipolar standard type)	2100	18·03	1	2·62	0·625	4·7
	1600	34·75	10	6·75	1·5	4·2
Slow speed multi-polar ring	..	..	100	15·75	4·1	3·8
	..	..	1000	36·	15	2·4
"Manchester" (ring) (1887)	1600	26	4·5	3·75	1·4	2·68
Ferranti alternator (star-disk) (1883)	1700	28	7·5	9	1·5	6
				5·25	1·25	4·5
Kapp	780	34	22·5	10	2·25	4·4
				8·5	2·25	3·77
Brown	200	44	100	14	3·5	4
Brown continuous current (1890)	500	56	26	9·75	2·0	4·88
				9·75	2·5	3·9
Ferranti alternator (1889)	120	85	1000	57	14	4
Mordey alternator (Field-magnet revolving)	500	53·75	75	13	4·5	2·88
				13	4	3·25
Mordey (1894)	150	100	800	45	11·5	4
Parsons Turbo-alternator	3000	..	350	12	2·3	5·2

on its core, and in belt-driven machines by the lateral drag of the pulley. When running, it is also subjected to bending stresses if the masses it carries are not properly balanced. If the brasses of the bearings keep the journals in line, it is evident that all such actions tend to bend the shaft at definite points. In machines with discoidal armatures a greater length of shaft is free to bend than in those with drum and cylindrical ring-armatures, which stiffen the middle portion. Professor Perry calculates for discoidal armatures,

$$l / d = n \sqrt{L} \div 1000\,;$$

and for drum- and elongated ring-armatures,

$$l / d = (n \sqrt{L} \div 3500) + 2,$$

where L is the length of the shaft between the middle points of its bearings, in inches; and n, l and d as before.

Journals, if plain, are usually terminated by collars or raised shoulders, to bear against the brasses and limit end-play. In some forms of machine end-play is specially provided for, so as to cause an even wear at the commutator.

In some British machines, chiefly small ones, and others of American make, a shaft of the same diameter throughout is used, with collars shrunk on to prevent end-play. This is not good engineering. A shaft ought to be as thoroughly designed for its work as any other part of the machine. It is well recognized in machine design that where an axle has to bear a transverse load tending to bend it between the points of support, it must be thickest where the bending moment is greatest. One takes as a basis of calculation the diameter appropriate at the journals (found as above) and assuming that the shaft is of circular section, calculates the diameters at the other parts by the rule that the diameter at each point should be proportional to the cube root of the bending moment at that point.[1] It must not be forgotten that where key-ways are to be subsequently cut for securing the spiders or other attachments, additional diameter must be given to admit of this without reduction of strength. An example of an excellent

[1] See Unwin's *Machine Design*, 147.

piece of design is afforded by the shaft of Brown's dynamo, Plate IV.; also by those of Kapp's dynamo, Plate II.; and of Mordey's dynamo, Fig. 283.

In the first of these examples it will be observed how the armature spiders fit on over the middle portion of the shaft, and the whole is tightened up by a threaded nut against a collar on the shaft. The commutator is built up around another and shorter sleeve, which slips over a slightly reduced part of the shaft, on the other side of the collar. The pulley is within the bearing, not overhung.

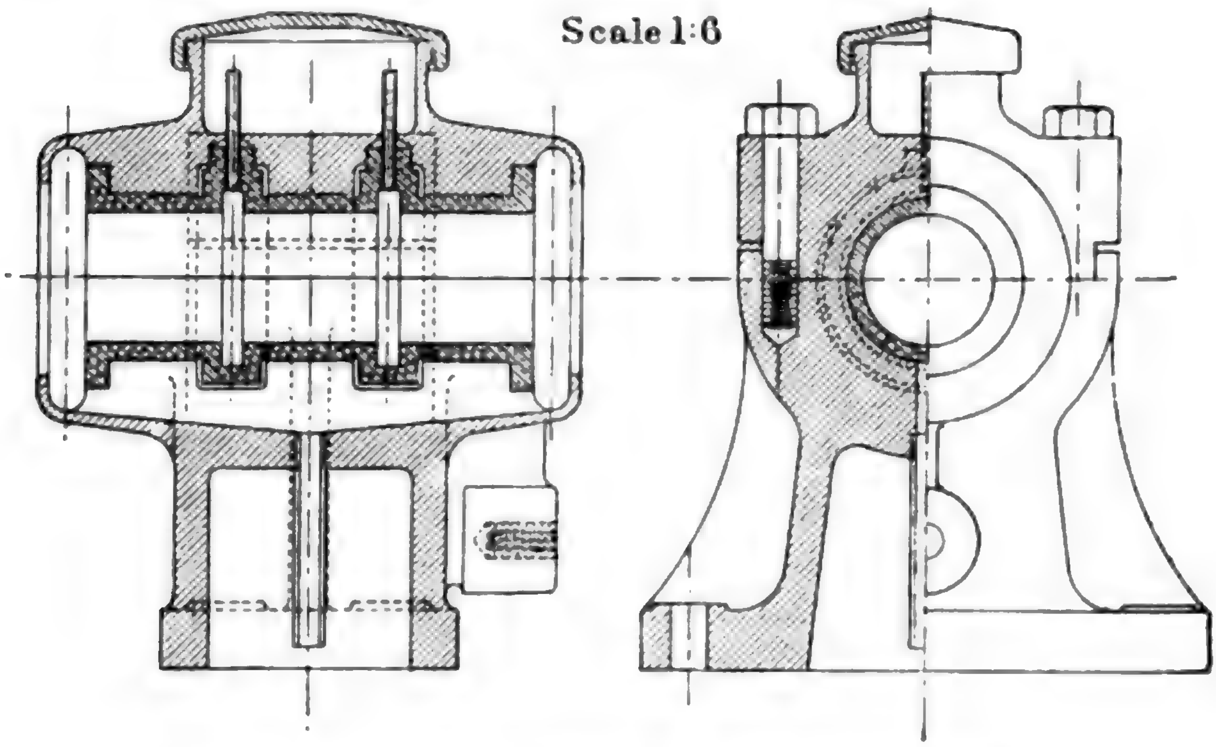


FIG. 253.—THRUST BEARING OF KAPP ALTERNATOR.

In the second, the armature spider is a long sleeve of cast iron, which stiffens the middle portion of the shaft, and is held up by a threaded nut against a collar.

Bearings and Pedestals.—Bearings for dynamos are always made divided, so that the armature can be lifted from its bed, and usually with steps of brass or gun-metal seated in an appropriate pedestal. Those who are not familiar with this elementary part of machine design should examine the drawings of the pedestals and bearings of various machines; particularly those of the Kapp dynamo, Plate I.; and those of Plate XVIII. and Figs. 273 and 277. Often the pedestal is

made in two parts bolted together; the joint occurring at the level of the under side of the armature to admit of the latter being withdrawn, and affording a resting point during removal. Where long bearings are used they are occasionally made of cast iron instead of gun-metal or brass. More often a soft-metal bearing is used; or rather a soft alloy, such as Babbitt's metal or "Magnolia" metal, is used as a lining for a step of gun-metal or cast iron; such antifriction metal being cast into shallow recesses formed for that purpose in the hollow of the step.

FIG. 254.—BALL BEARING (AUTO MACHINERY COMPANY).

Ball Bearings.—With the introduction of machinery of precision for making steel balls for antifriction bearings, the use of the latter for dynamos has been coming into favour. Fig. 254 gives a view of a bearing of this class, and shows the disposition of the balls between the revolving liner and the outer stationary rings. For motor-generators, where there is no lateral drag due to belts, these bearings have been found excellent.

Thrust Bearings.—In all dynamos with disk or discoidal ring-armatures, end-play is inadmissible; and thrust-bearings

must be provided similar to those used on screw propeller shafts with raised collars on the journals. Or, instead, the shaft may be constructed with shoulders somewhat deeper than usual at the journals, to bear against the brasses. The reader should examine the various thrust-bearings in the drawings of the following dynamos: Mordey - Victoria, Fig. 283, p. 418; Ferranti alternator, Fig. 417. That of the Kapp alternator, built by Messrs. Johnson and Phillips, is shown in Fig. 253.

Spherical Bearings.—With all long bearings it is of great importance that they should not only be exactly concentric,

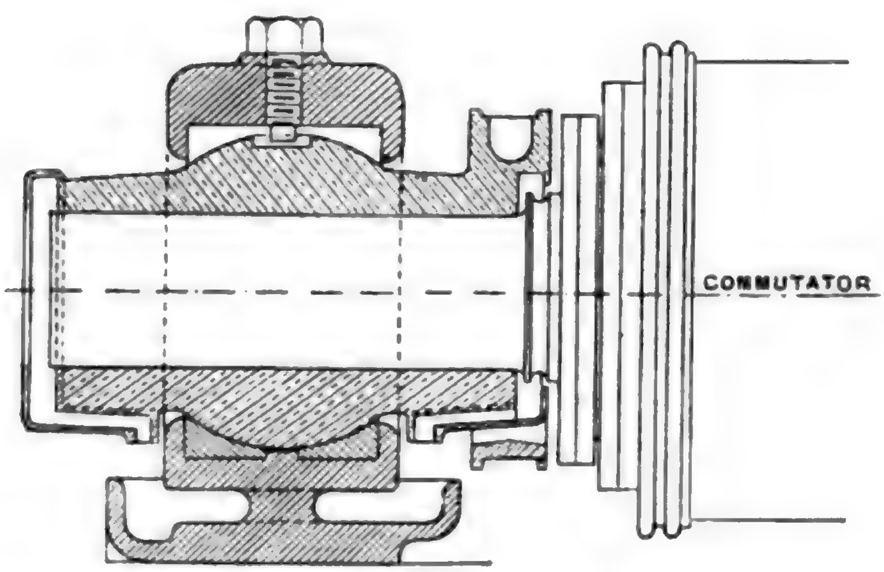


FIG. 255.—SPHERICAL BEARING OF GOOLDEN DYNAMO.

but that they should also be accurately in line. To permit the steps to adjust themselves to perfect alignment it is now a frequent practice to provide them with a spherical seat; that is to say, a spherical or nearly spherical shape is given to the enlarged central portion of the bearings, and this spherical portion is provided with a soft metal seat on the pedestal.[1] Fig. 255 gives a design by Mr. Ravenshaw. The bearings of the Westinghouse alternator closely resemble Fig. 255, but are adapted to longer journals.

Lubricators.—Provision must be made for lubricating

[1] See paper by Mr. Coleman Sellers, in *Journal of Franklin Institute* for 1872, or *Engineering*, xv. 17, or the figure in Unwin's *Machine Design*, p. 170.

bearings with a due supply of oil or grease, and arrangements to prevent waste and spilling. It is usual to provide an oil-well in the hollow casting of the pedestals, into which the oil drains from the ends of the brasses. Sight-feed lubricators which supply the oil visibly drop by drop are undoubtedly best for ordinary machines. Such a lubricator is illustrated in Fig. 256. The lever C at the top closes the feed of oil when the machine is not wanted to run. The collars A and B regulate the rate at which the oil flows down to drop through the tube-sight below. For ship dynamos special forms that cannot spill oil are preferable. It is usual to provide a collar on the journals to collect and throw off the oil centrifugally, the lips of the bearing being carried (as shown in Fig. 255, above) beyond the brasses, and provided with a re-entrant rim which catches the oil and returns it to the well below. Sight-drain lubricators which permit the oil that flows from the bearings to drop visibly are in some cases preferable. For large dynamos, where there is great weight on the bearings, special precautions have to be taken, as in the lubrication of the bearings of propeller shafts. Oil is supplied under pressure, sometimes from two independent sources, to prevent risk of failure. Such arrangements are the more needful in the case of dynamos, because the motion is one of pure rotation, the shaft not being subjected, like the crankshaft of a steam engine, to alternate lateral thrusts, which help to work the oil in under the journals. Sellers has

FIG. 256.—VISIBLE DROP-FEED LUBRICATOR.

proposed a double lubrication[1] as a safeguard. The ordinary lubricator supplies oil at the centre of the bearing, and the top brass is provided near each end with a cup containing a stiff mixture of tallow and oil, which only melts in case the bearing heats from failure of the ordinary oil supply. Self-lubricating devices are sometimes used, an oil-well being provided in the lower brass, into which dips a collar on the journal, or a metal ring running loosely over it, or even a mere ring of felt. (See Brown's motor, Plate XVIII.) Fig. 257 represents the self-oiling arrangement used in their small motors by the Crocker-Wheeler Co. of New Jersey. Some makers provide spiral grooves in the soft-metal lining of the bearing, so that the oil brought up by the ring is distributed along the journal.

FIG. 257.—BEARING WITH SELF-OILING RINGS.

For dynamos and alternators of the "umbrella" type, with vertical shafts for use with turbines, very special oiling arrangements must be used on account of the very great weight on the bearings. (See Plates VI. and XVI.) Arrangements are made in all large machines of this type to take a large portion of the dead weight off the bearing surfaces, by means of hydraulic floats, or in some cases by applying electromagnets to produce an upward pull. In the case of the great Niagara alternators, Fig. 432, the lubrication is effected by oil placed in a large cast-iron cup several feet in diameter attached to the shaft below the bearing. Into the oil dips a stationary tube, up which, when the cup revolves, the oil rushes to the top of the bearing. A cold-water circulation is provided for artificial cooling.

---

[1] Unwin's *Machine Design*, 171.

Keys and Feathers.—Keys for securing the armatures and pulley to the shaft should be of the sunk or flat type, not of the saddle type, which is less reliable. The rules for keys are as follows: b meaning breadth; t thickness; and d diameter of the eye of the hub, all in inches—

$$b = \tfrac{1}{4}d + \tfrac{1}{8}'' ;$$
$$t, \text{ for sunk keys } = \tfrac{1}{10}d + \tfrac{1}{8}'' ;$$
$$t, \text{ for flat keys } = \tfrac{1}{11}d + \tfrac{1}{16}'' ;$$

Where two or more feathers are used on different sides of the shaft, the breadth of each may be somewhat less than this. For small machines these numbers are needlessly large.

Pulleys and Belts.—There is no need to give special rules for these, as the ordinary rules for running machinery apply.

Bed-plates.—In designing bed-plates it is usual to save weight of metal by coring out and leaving stiffening ribs and flanges. All this is quite right except in those cases where any part of the bed-plate serves also a magnetic purpose and constitutes a part of the magnetic circuit. For example, in the Kapp dynamo, Plate I., the bed-plate serves partially as a yoke for the field-magnet; and in the "Manchester" dynamo of Mather and Platt, Fig. 285, p. 421, as also in Brown's dynamo, Plate IV., the part of the casting which passes under the armature must be left solid. British makers usually design bed-plates of box-pattern. In the case of machines with drum or cylindrical-ring armatures it is convenient to be able to withdraw the armature longitudinally by removing one pedestal, which therefore should be a separate casting. In that case, for machines of the over-type, it is convenient that the pedestal should be made removable down to the level of the under side of the armature, so that when the upper part is removed the stump may form a convenient resting place for the armature in removal. A case is shown in Fig. 273, p. 401, and in the Kapp dynamo, Plate I.

Couplings.—When dynamos are driven without belting from the steam engine on the same bed-plate, it is frequent to

connect their respective shafts by a coupling. Of these devices there are several special patterns, such as Brotherhood's, with a connecting part of leather, and Raworth's with flexible steel bands, admitting of a certain amount of play if the two shafts are not in exact alignment. It is well to construct the coupling so that it also insulates the engine from the dynamo.

CHAPTER XVI.

ELEMENTS OF DYNAMO DESIGN: CALCULATION OF CONTINUOUS-CURRENT DYNAMOS.

THE symbols used in this chapter are described on p. 169.

As in all designing of machines, so with the designing of dynamos, experience is the ultimate guide. Before we can begin to design a dynamo we must know what we want: how many amperes it is to give, and at what voltage. We must also have definite ideas as to the intended speed of running. To design a machine which, when driven at a prescribed speed, shall yield any desired number of amperes of current at any given voltage, is a very simple matter to an engineer who has already had experience in designing dynamos of the same general type, but of different output. To a man who has designed 2-pole continuous-current machines for incandescent lighting it is a simple matter to design another machine of the same sort. But it would be to him by no means so easy from this experience only to pass to designing machines of a multipolar type, or to design alternate-current machines.

Happily a vast quantity of data are available respecting good machines of many types and sizes. Tabulated statistics of the results of experience are invaluable to the designer. Foremost of such statistics are those to be found in a series of articles by Mr. Wiener in the *Electrical World*, in the years 1894 and 1895. Many points need no such data, but may be found from first principles.

It is known, for example, that the number of watts of output of a dynamo of given form, at a given speed, is approximately proportional to its weight. For example: given a dynamo which at 720 revolutions per minute yields (without sparking or overheating) 200 amperes at 105 volts (a 21 kilowatt machine), it is known that using the same iron

carcass, and rewinding the machine with new coils equal in weight to those previously used, the machine may be made to give (at same speed as before) 300 amperes at 70 volts, or 250 amperes at 84 volts, or 30 amperes at 700 volts—the products in each of these cases being 21,000 watts. A machine for double the output would have double the weight of iron and double the weight of copper, approximately, if of the same type.

Also, since the voltage is proportional to speed, if a new dynamo had to be designed to give the same output at a speed of 480 instead of 720 revolutions per minute, a carcass about 1½ times as heavy would be required. A manufacturer who had in stock carcasses of various sizes would, of course, select the nearest size and wind it with an appropriate winding.

The first stage in understanding the subject is to examine carefully the design of some well-established machines, and to see how the dimensions of their several parts are adapted to their functions. It will then be an easier matter to work out any case for a fresh type of machine. But that we may know what sort of data are needed from experience, let us make a preliminary attempt at calculating a design. Calculations are needed to ascertain the proper sizes of the parts. Some of these calculations are purely electrical, others magnetic, others mechanical, and some are of a wholly empirical nature founded on experience. If a dynamo is to be constructed to give, say, an output of 200 amperes at 55 volts, the conditions respecting safety from overheating practically determine the size of wire that can be used for the prescribed current: no calculation being needed beyond a reference to a wire-table, and the knowledge that in armatures of dynamos it is usually quite safe to allow 2000 or more amperes to the square inch. Suppose we settle on a stranded wire of 7 No. 13 S.W.G., which will safely carry 100 amperes (each conductor carries only *half* the armature current). If, however, the field-magnet is shunt-wound, as it must be for ordinary lighting at constant pressure, there will be additional amperes to allow for besides the 200 for the lamps. Let it be taken that 5 amperes, or 2½ per cent. of the current, will suffice. Suppose this all settled, then the question arises of the 55 volts. What size

of armature, what winding of it, what size of field-magnet will be required; and how must the latter be wound so as to give what is required at the proper speed? Again, it must be remembered that if 55 volts is to be the pressure at the mains, the armature must generate more volts than this—say 57 or 58—to allow a margin for the "lost" volts (p. 181). Suppose this settled, then what is the next step?

Consider the fundamental equation of the continuous-current dynamo (see pp. 46 and 171).

$$E = n Z N \div 10^8.$$

Now if we assume that the speed n is prescribed beforehand, this formula tells us that the volts of the armature depend on Z, the number of armature conductors employed (i. e. on the weight of copper), and on N, the number of magnetic lines through the armature (i. e. on the cross-section of the iron core, and on the degree to which its magnetization is forced up). In the case in question, suppose the prescribed speed to be 1140 revolutions per minute, then n (the revolutions per second) = 19. And if E is taken at 57, it follows that Z N multiplied together must come to 300,000,000. But how much must Z and N be separately? Well, experience shows that in such machines as this is to be, each armature-section should consist of one, or, at most, two turns, whether wound as ring or as drum. Experience also shows that for 2-pole machines it is convenient if the number of sections (and therefore of bars in the commutator) is a multiple of 6. Also experience shows that if there are fewer sections than 30 there will be fluctuations and possibly spark troubles, and that if there are so many as 150 or upward, there comes in great expense in the construction. We might take 42, or 48, or 54, or 60, or 72, and work out a design on any of these. It is very easy, on completing the calculations, to try another set if the first do not seem quite satisfactory. If there is only one convolution in each section, and the armature is ring-wound, Z will be the same as the number of bars of the commutator; but if drum-winding is adopted, then Z will be numerically twice as great. Now if Z is small, N will be large,

and *vice versâ;* and we know that to secure sparkless running it is well to keep N large and Z small (p. 95). Suppose, then, we take Z at 72, so that when wound drum-wise there will be 36 sections and a 36-bar commutator. Clearly this will involve that N shall equal $300{,}000{,}000 \div 72 = 4{,}166{,}600$; in round numbers there must be a flux of 4,170,000 magnetic lines through the core of the armature. Again, experience shows that the proper degree of magnetization to allow in armatures of such machines is (see p. 368) from 15,000 to 17,000 lines to the square centimetre, or say from about 90,000 to 100,000 lines to the square inch. To carry the 4,170,000 lines the armature core ought then to have a nett cross section of about 45 square inches, or, say, 288 square centimetres. But here again comes a choice. How shall we determine this cross-section? What size of core-disk shall we choose, and what total length of core-disks shall we pack together along the shaft? Shall we use a toothed, or a smooth core-disk? Suppose we decide to use smooth cores. If we take large core-disks of great radial depth we shall only need a comparatively small number of them, and our armature will be short; whereas if we take small core-disks we shall have a long armature. Here two other considerations come in to influence our decision. We have provisionally settled the gauge of copper conductor to carry our current—a stranded wire of 7 No. 13's, of which 3·38 turns will lie side by side in the breadth of an inch. If there are to be 72 such conductors all in one layer, they will occupy about 21 inches side by side. If we allow nothing extra for inserting driving-horns, this will involve core-disks about 7 inches in external diameter. If we say $7\frac{1}{4}$ inches with a $4\frac{1}{4}$-inch hole, the doubled radial depth of iron will be 3 inches; and as there are to be 45 square inches of section of iron that will require a total length of about 15 inches, or, with the insulation between the core-disks a length of 16 inches, the core of the drum will then be about twice as long as its own diameter. It is usual in drum-cores to make the length a little greater than the diameter; but this will do for present purposes. But there is another consideration. If we have got so many complete convolutions of

conductor as 36, and each conductor carries 102½ amperes, there will be for total cross-magnetizing effect a product of 3690 ampere-turns. Will this, on the core-disk of 7¼ inches diameter, be too great—that is to say, so great as to cause sparking? This is purely a question for experience to decide (see p. 385). Now experience shows that in 2-pole drum-wound machines a core-disk 7¼ inches in diameter will carry at least 5200 ampere-turns without sparking, so that we are well within the limit of sparklessness. We might diminish internal resistances a little by choosing a smaller core-disk, so as to make a longer core that will waste less wire in wrapping across the ends; but in that case we cannot use the stranded wire first selected. If, for example, we choose 6-inch core-disks with 2-inch holes, we should require a nett length of 12 inches, or a gross length of nearly 13 inches. And we could not fit the 72 conductors around the periphery unless these were specially made, say of drawn copper strips placed three side by side (as in Fig. 258*a*), each strip being in section 250 mils wide by 60 mils thick. The three overspun together would be about 210 mils thick; and the seventy-two would occupy about 15 inches around the periphery of the 6-inch disk, leaving 3·8 inch for the insertion of driving-horns. Another way of winding would be to use, with 7¼-inch core-disks, four wires in parallel, instead of the stranded conductor, each wire being a No. 10 S.W.G., carrying 25 amperes, arranged two deep, there being 144 around the periphery, and occupying about 22 inches side by side, as in Fig. 258*b*; a third method would be to use a toothed core-disk $8\frac{3}{16}$ inches in diameter, with 72 teeth, with wires of rectangular section

FIG. 258*a*.

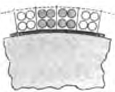


FIG. 258*b*.

FIG. 258*c*.

two deep sunk between the teeth, the size of each strip being $\frac{1}{8}$ inch thick and $\frac{1}{5}$ inch wide, as in Fig. 258*c*. If the manufacturer had in stock no core-disks of these sizes, but had some of 7-inch, he would probably use these, and select a wire to suit. The difference in the final efficiency of the machine would be trifling.

Assume then that as the result of all these considerations the $7\frac{1}{4}$-inch core-disks have been chosen, that the armature core is 15 inches long, and that the insulation and copper windings and binding wires will bring up the external diameter to about $8\frac{1}{8}$ inches—it yet remains to design the field-magnet.

We will settle upon the form of Fig. 102 as the type, and construct the horizontal limbs of cast iron. We must, provisionally at least, assume a value for the leakage coefficient, which in this type is rather high, say 2·0. Hence we must design the field-magnet to carry 8,340,000 magnetic lines instead of 4,170,000. And, as experience shows that it is not well to force the magnetization beyond about 7000 lines to the square centimetre or 43,000 to the square inch, this implies a cross-section of at least 194 square inches, or about 1191 square centimetres. Again, experience shows that it is well if the armature-core extends a trifle beyond the field-magnet on each side. This can be attained by bevelling the edges of the polar parts while keeping the rest broad. Suppose the field-magnet limbs to be made $16\frac{1}{2}$ inches wide from front to back, and $11\frac{1}{2}$ inches in depth; then what length must they be? Obviously a sufficient length to leave room between them for the wrought-iron core and the bobbin large enough to hold the proper amount of winding necessary to excite the magnetization to the prescribed degree. To ascertain the amount of wire that is requisite one has first to calculate the number of ampere-turns by the principle of the magnetic circuit. But how can we apply the principle of the magnetic circuit without knowing the length of iron that is to be used? The method usually adopted here is one of approximation. Make a preliminary calculation in which a rough estimate is inserted for the yet undetermined length

of the iron limbs. Having done this, see whether, without mechanical difficulty or risk of overheating, the quantity of wire thus calculated can be wound upon the length of limb so assumed; and having made this comparison, then diminish or increase the length chosen for the limb, and recalculate. But here again comes in a complexity. If we assume that the armature has no demagnetizing reaction, we shall find our calculated quantity of wire much below the quantity actually required. Therefore, calculate approximately by the rule given on p. 231 the number of demagnetizing ampere-turns, and add 2·0 times this to the number previously found; for the field-magnet must be made long enough to carry this additional number of coils. In the case under consideration assume the polar angle to be 145° on each side, it follows that $\frac{145}{180}$ of 72, or about 58 of the conductors of the armature, will be in the gap-spaces at any one moment, and that there will be a belt of conductors (see Fig. 70, p. 85), seven broad, exposed between the tips of the poles. This gives us 700 ampere-turns of demagnetizing power if the brushes are assumed to be set near the pole-tips.

Now the external diameter of the armature is $8\frac{1}{8}$ inches, and we must allow $\frac{1}{8}$ inch clearance all round, making the diameter of the bored polar surface $8\frac{1}{4}$ inches, and the actual gap-space from iron to iron $\frac{1}{2}$ inch. The gap-spaces themselves may be taken as being $10\frac{3}{4}$ inches along the curve, and 15 inches from back to front. We are now ready for the rules by which to calculate the field-magnet design. Hence we may pause here in these general considerations, which have been followed far enough to show the need for handy formulæ of sufficient exactness.

Electrical Calculations.

§ 1. *To calculate the Lost Volts in the Armature.*—Take the number of amperes C_a flowing through the armature; multiply this by the number of ohms (or fraction of an ohm) that represents the internal resistance of the armature.

$$\text{Lost volts} = r_a \times C_a.$$

A similar mode is to be used for calculating the volts lost by resistance in any coil in series with the armature. If the other internal main-circuit resistances, such as a series coil, are called r_m, we must add this to r_a and get

$$\text{Lost volts} = (r_a + r_m) \times C_a.$$

§ 2. *To calculate the Current going through Shunt.*—Divide volts e at terminals by number of ohms of resistance r_s of shunt coil.

$$C_s = e \div r_s.$$

In a good modern machine C_s may be taken as about 20 to 15 per cent. of C in machines of less than 1 kilowatt; 10 to 5 per cent. in machines of 1 to 10 kilowatts; 5 to 2½ per cent. up to 200 kilowatts; 1½ per cent. in machines of 1000 kilowatts (or less).

§ 3. *To calculate the Whole Current flowing through Armature.*—Add to the number of amperes C that flow to the lamps, the number of amperes C_s flowing around the shunt coil.

$$C_a = C + C_s$$

Or a percentage (as above) may be added to the current to be supplied to the mains.

§ 4. *To find the Gauge of Wire needful for the Armature.*—Remembering that there are in bipolar machines two paths through the armature, divide C_a by 2, and then refer to the *Amperage and Wire-Gauge Table* (Appendix A), and select a wire if it is to be a wire winding; otherwise a stranded bar will be chosen. Remember that in very small machines it is safe to go up to 4000 amperes per square inch, and in large machines to 2000 amperes per square inch.

§ 5. *To find the Whole Electromotive-force* E *that must be generated in the Armature of a Dynamo.*—Ascertain the number of volts of pressure e, at which the mains are to be supplied from the terminals of the dynamo (depending on the lamps that are to be used): to this add the calculated number of *lost volts.*

$$E = e + r_a C_a.$$

§ 6. *To calculate the number of Armature Conductors* Z.—This is a matter of experience: see p. 313 above, and p. 342.

§ 7. *To calculate the Electromotive-force in the Armature. (Continuous Current Machines.)*—Multiply together the revolutions per

second n, the number of armature conductors Z, and the magnetic flux N, then divide by one hundred million. For :—

$$1 \text{ volt} = 10^8 \text{ C.G.S. units of electromotive-force.}$$

$$E \text{ (volts)} = \frac{n Z N}{10^8}$$

[Example: a certain Phœnix dynamo. $n = 23 \cdot 6$; $Z = 180$; $N = 2,530,000$. Find E.] For multipolar machines one must also divide by the number of bifurcations of circuit. For armatures not internally cross-connected this will be half the number of brushes (see p. 257).

Efficiency Calculations.

§ 8. *To calculate the Wasted Power in a Dynamo.*—To calculate horse-power from the watts divide the number of watts by 746.

(1) Watts wasted in armature coil. Multiply volts lost in armature by amperes in armature: or multiply resistance of armature by square of armature current.

(2) Watts wasted in series coil. Multiply volts lost in series coil by amperes in that coil: or multiply resistance of coil by square of amperes in that coil.

(3) Watts wasted in shunt coil. Multiply amperes in shunt by volts at terminals of shunt: or divide square of volts at terminals by resistance of shunt coil.

(4) Watts wasted by eddy currents not calculable directly.

(5) Watts wasted by magnetic hysteresis. The formula and table of hysteretic constants given on p. 140 will give the number of watts wasted by hysteresis in well-laminated soft-wrought iron, when subjected to a succession of cycles of magnetization as in the rotating armature core of a dynamo.

§ 9. *To calculate the Electrical Efficiency.*—Multiply together the useful current C and available volts e, and so obtain the useful watts. Multiply together the total current C_a and total electromotive-force E, and so obtain the total watts of gross output. The electrical efficiency is the ratio of the former to the latter.

$$\eta = e\,C \div E\,C_a.$$

Or it may be calculated by dividing the useful watts by the total watts (useful and wasted added together). The electrical efficiency does not include waste by eddy currents, hysteresis, or friction.

§ 10. *To Ascertain the Commercial Efficiency.*—Calculate by rules

given on pp. 137 and 138 probable losses by hysteresis and eddy-currents in iron; and estimate losses by friction at bearings and by eddy-currents in copper from data of tests of machines of similar type. Then divide useful watts by total watts including these losses.

Magnetic Calculations.

§ 11. *To Calculate the Magnetic Flux through the Armature.*—Measure e, add lost volts, and so calculate E; then multiply by 10^8 and divide by n and by Z.

$$N = \frac{E \times 10^8}{n \times Z}.$$

[Example: An Edison-Hopkinson dynamo. $n = 12 \cdot 5$; $Z = 80$; $e = 105$; $r_a i_a = 3 \cdot 26$; find N.]

§ 12. *To calculate the Magnetic Flux-density* B *in an Iron Core.*—Ascertain the magnetic flux N through that core; and the nett cross-section A, of iron in that core. Then divide N by A.

$$B = N \div A;$$

or, if measures are given in square inches,

$$B_{''} = N \div A''.$$

[Example: in an Edison-Hopkinson dynamo N in armature = 10,826,000; A″ = 125 square inch; find $B_{''}$.]

[Example: in a Kapp dynamo N in armature = 6,730,000; A = 403·1 square centimetres; find B.]

§ 13. *To calculate the Cross-Section of Iron to carry a given number of Magnetic Lines.*—First determine how many is the total number of magnetic lines that must pass through the armature core when machine is at full work: call this N. Next, settle what is the advisable value to give to the flux-density B. In continuous current machines for incandescent lighting it is not usually advisable to push the magnetizàtion further than B = 17,000 (to the square centimetre), or $B_{''}$ = 110,000 (to the square inch). For arc-lighting machines the flux-density may be pushed further. For alternate-current machines a much lower density is desirable: B say = 7000. For cores of transformers a density of 2000 to 4000 is usual. Having settled the value of B or $B_{''}$, dividing N by the value settled will give the required sectional area A or A″.

[Example: in a certain Phœnix dynamo it was decided that $B_{''}$

should be 115,000 lines per square inch, and N had to be 2,606,000; find A″.]

[Example: in a Kapp alternator, A in the armature core was 103·2 square centimetres; assuming B = 6500; calculate N.]

For calculating the requisite cross-section of field-magnets a similar process is used, but allowance must be made for carrying a larger number of magnetic lines (because of magnetic leakage); and it is advisable to use, even with wrought-iron cores, a somewhat lower degree of magnetization. If cast-iron cores are used, the section will have to be nearly twice as great, as it is not advisable in that material to force in more than about 8000 lines to the square centimetre, or than about 50,000 to the square inch.

§ 14. *To allow for Magnetic Leakage.*—In consequence of magnetic leakage the magnetic flux is different at different parts of the magnetic circuit.

[Example: in an Edison-Hopkinson dynamo it was found that to get 10,826,000 lines through the armature, enough magnetizing power had to be put on to make 14,289,000 lines flow through the field-magnet, 3,464,000 of these leaking away and not going through the armature. This is as if out of every 132 lines in field-magnet, 100 only were useful and 32 wasted.]

The symbol for the coefficient of allowance for leakage is v. Its value varies in different dynamos from 1·2 to 2 or more. In the example above given $v = 1 \cdot 32$. Allowance must be made for v times N magnetic lines in the field-magnet in order that there shall be a flux of N lines through the armature. (Compare p. 151.)

§ 15. *To find the Permeability of Iron at any stage.*—Refer to tables or curves (such as those given on pp. 125 and 138) relating to the particular brand of iron under consideration.

[Example: in armature of Kapp dynamo, when running on open circuit N = 6,730,000; A = 403·1 square centimetres; find B; and from this, assuming the curve for the iron to be the same as the uppermost curve in Fig. 85, find μ. Also find B and μ, when, at full load, N is increased up to 7,170,000 by the added magnetizing action of the series coil.]

[Example: in field-magnet (cast iron) of a Phœnix dynamo A″ = 62 square inches; N in armature = 2,606,000; v (leakage allowance coefficient) = 1·36. Calculate v N, then $B_{\prime\prime}$; then find μ by reference to Table II., p. 126, for cast iron.]

CALCULATIONS RESPECTING MAGNETIC CIRCUIT.

Fundamental Law of Magnetic Circuit.

Magnetomotive-force $\div$ magnetic reluctance $=$ the magnetic flux; or, inversely, thus:—

§ 16. *To calculate the Magnetomotive-force requisite to force a given number of Magnetic Lines through a Definite Magnetic Reluctance.*—Multiply the number which represents the magnetic reluctance by the number of magnetic lines that are to be forced through it. The product will be the amount of the magnetomotive-force.

If the magnetic reluctance has been expressed on the basis of centimetre measurements, the magnetomotive-force, calculated in this way, will require to be divided by 1·257 (i.e. by $4\pi/10$) to give the number of ampere-turns of requisite magnetizing power.

§ 17. *To calculate Reluctance of an iron core.*

(*a*) *If dimensions are given in centimetres.*—Magnetic reluctance being directly proportional to length, and inversely proportional to sectional area, and to permeability, the following is the formula:—

$$\text{Reluctance} = l \div A\,\mu\,;$$

but the value of μ cannot be inserted until it has been calculated from B as above in § 15.

(*b*) *If dimensions are given in inches.*—In this case we apply a numerical coefficient, which takes into account the change of units (2·54 centimetres to the inch), and also, at the same time includes the operation of dividing the magnetomotive-force by $\frac{4}{10}$ of π ($=$ 1·257) to reduce it to ampere-turns. So the rule to find the reluctance becomes:—Divide the length (in inches) by the area (in square inches), and by the permeability (formed as above from $\mathsf{B}_{''}$), and then multiply by 0·3132. Or in symbols:—

$$\text{Ampere-turns per line} = \frac{l''}{A''\,\mu} \times 0{\cdot}3132.$$

[Example: find the magnetic reluctance from end to end of a bar of wrought iron 10 inches long, with a cross-section of 4 square inches, on the supposition that the magnetic flux (N) through it will amount to 440,000 lines.]

§ 18. *To calculate the Total Magnetic Reluctance of the Magnetic Circuit of a Dynamo.*—This is done by calculating the magnetic reluctances of the separate parts and adding them together. Account

must, however, be taken of magnetic leakages by allowing for v N lines in the field-magnet cores and yoke.

In the simplest case the magnetic circuit consists of three parts: (1) iron in armature core; (2) air, copper, cotton, &c., in gap-spaces; (3) iron in field-magnet. The permeability of the materials in the gap-spaces may be taken as = 1. Hence the three reluctances in question are respectively written:—

	For centimetre measure.	For inch measure.
1. Armature	$\frac{l_1}{A_1 \mu_1}$	$\frac{l''_1}{A''_1 \mu_1} \times 0{\cdot}3132$
2. The Gap-spaces	$\frac{2l_2}{A_2 \mu_2}$	$\frac{2l''_2}{A''_2 \mu_2} \times 0{\cdot}3132$
3. Magnet core ..	$\frac{l_3}{A_3 \mu_3}$	$\frac{l''_3}{A''_3 \mu_3} \times 0{\cdot}3132$

19. *To calculate the Ampere-turns of Magnetizing Power Requisite to Force the Desired Magnetic Flux through the Reluctances of the Magnetic Circuit.*

(*a*) *If the dimensions have been given in centimetres,* the rule is:—

Ampere-turns = magnetic flux multiplied by the magnetic reluctance, divided by $\frac{4}{10}$ of π (= 1·257);

or, in detail, the three separate amounts of ampere-turns required for the three principal magnetic reluctances of a dynamo are expressed as follow:—

Ampere-turns required to drive N lines through iron of armature $\Big\} = \mathrm{N} \times \dfrac{l_1}{A_1 \mu_1} \div \dfrac{4\pi}{10};$

Ampere-turns required to drive N lines through the two gap spaces $\Big\} = \mathrm{N} \times \dfrac{2\,l_2}{A_2} \div \dfrac{4\pi}{10};$

Ampere-turns required to drive v N lines through the iron of field-magnet $\Big\} = v\mathrm{N} \times \dfrac{l_3}{A_3 \mu_3} \div \dfrac{4\pi}{10};$

and, adding up:

$$\text{Total ampere-turns required} = \frac{10}{4\pi}\,\mathrm{N}\left\{\frac{l_1}{A_1 \mu_1} + \frac{2l_2}{A_2} + \frac{vl_3}{A_3 \mu_3}\right\}.$$

(*b*) *If the dimensions are given in inches*, the rule is:—

Ampere-turns = magnetic flux multiplied by magnetic reluctance;

or, in detail:

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \quad \mathsf{N} \text{ lines through iron of}\\ \quad \text{armature}\end{array}\right\} = \mathsf{N} \times \frac{l''_1}{A''_1 \mu_1} \times 0{\cdot}3132;$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \quad \mathsf{N} \text{ lines through two gap}\\ \quad \text{spaces}\end{array}\right\} = \mathsf{N} \times \frac{2l''_2}{A''_2} \times 0{\cdot}3132;$$

$$\left.\begin{array}{l}\text{Ampere-turns required to drive}\\ \quad v\,\mathsf{N} \text{ lines through iron of}\\ \quad \text{field-magnets}\end{array}\right\} = v\mathsf{N} \times \frac{l''_3}{A''_3 \mu_3} \times 0{\cdot}3132;$$

and, adding up:

$$\left.\begin{array}{c}\text{Total ampere-turns}\\ \text{required}\end{array}\right\} = 0{\cdot}3132\ \mathsf{N} \left\{\frac{l''_1}{A''_1 \mu_1} + \frac{2l''_2}{A''_2} + \frac{v l''_3}{A''_3 \mu_3}\right\}.$$

[Example: in a certain Lahmeyer dynamo, with cast-iron magnets, the following were the data: $\mathsf{N} = 2{,}328{,}000$; $v = 1{\cdot}11$; $l''_1 = 6\frac{9}{32}$; $l''_2 = \frac{13}{64}$; $l''_3 = 40$; $A''_1 = 34{\cdot}8$ sq. in.; $A''_2 = 69{\cdot}5$; $A''_3 = 86{\cdot}5$: calculate the required ampere-turns.]

In some forms of dynamo the magnetic reluctances of pole-pieces and yokes must be separately calculated; and allowance must in some cases be made for leakages at different parts of the circuit. Hence a more careful formula would be:—

$$S\,C = 0{\cdot}3132\ \mathsf{N} \left\{\frac{l''_1}{A_1 \mu_1} + \frac{2l''_2}{A_2} + \frac{v_3 l''_3}{A_3 \mu_3} + \frac{v_4 l''_4}{A_4 \mu_4} + \frac{v_5 l''_5}{A_5 \mu_5}\right\}$$

It is expedient that the calculation of the ampere-turns should be made *twice*; that is once (using the value of N that corresponds to the case of no lost volts) to find the value of the ampere-turns of winding to be put on the shunt, when there is no current through the lamps; and once (using the higher value of N that corresponds to the maximum E) to find the increased ampere-turns that are required when the full current is being taken from the armature. These will have to be provided for (in compound-wound machines) by a series coil to compensate for demagnetizing effect of armature, as well as for the lost volts.

§ 20. *To Estimate the Additional Ampere-turns Required to Compensate for the Demagnetizing Action of the Armature Current when the Brushes have a Forward Lead.*

Count the number of conductors on periphery, between the diameter of symmetry and the actual diameter of commutation, and multiply by C_a the amperes flowing through armature. The product so found will have to be increased by a certain amount on account of the drop in magnetic potential which takes place in the field core owing to the increased magnetic leakage and decreased permeability of the core. This cannot be estimated without going over the magnetic calculations in the manner shown on p. 365: in practice the product must be increased from $1\frac{1}{2}$ to 2 times. For ring machines the product must be doubled. The number so determined must then be added to the number of ampere-turns previously calculated.

Examples of Calculations applied to Continuous-Current Dynamos.

As remarked at the opening of the present chapter, it is advantageous to go over the calculation of some existing machines. Two complete examples are given here, one relating to an Edison-Hopkinson dynamo (see pp. 148, 152, and 403); the second to a Kapp dynamo, Plates I. and II. The magnetic-circuit calculations for the first have been calculated out in C.G.S. units; those in the second in inch units, so as to show both modes of calculation. As a third example, an exercise for calculation is given.

Example I.—An Edison-Hopkinson Dynamo.

Description adapted from paper by J. and E. Hopkinson, in *Phil. Trans.*, 1886. (See Fig. 287, p. 422.)

Shunt-Wound Dynamo, with Drum Armature: 33 kilowatts Output: 320 Amperes, at 105 volts, at 750 revolutions per minute.

Armature: Built up of about 1000 iron core plates stamped out of soft sheet iron separated by sheets of paper, and held between two end-plates, one of which is secured by a washer shrunk on to the

shaft, and the other by a nut and a lock-nut screwed on shaft itself. Shaft of Bessemer steel, insulated before core-plates are threaded on.

Core-disks external diam.	$9\frac{5}{8}$ inch,	24·5 centim.
" internal diam.	3 "	7·62 "
Shaft diam.	$2\frac{3}{4}$ "	6·985 "
Radial depth of iron	$3\frac{5}{16}$ "	8·45 "
Gross length of core	20 "	50·8 "
Total thickness paper insulation ..	$1\frac{3}{8}$ "	3·4 "
Nett length of iron in core	$18\frac{5}{8}$ "	47·4 "
Nett cross section of iron	$123\frac{1}{16}$ sq. in.	801 sq. cm.
Ditto allowing for shaft	125 "	810 "

Core is wound with 40 convolutions (i. e. there are 80 external conductors at periphery), each consisting of 16 strands of copper wire 69 mils or 1·753 millimetres in diameter (i. e. $15\frac{1}{2}$ B.W.G.), the convolutions being placed in two layers of 20 each. Commutator, 40 bars of copper insulated with mica: connections to armature so made that plane of commutation is horizontal when circuit is open. Cross-section of the above wire, 0·0037 sq. in. or 2·3 sq. mm.; total ditto of each set of 16 wires 0·0592 sq. in., or 38 sq. mm. Resistance of armature from brush to brush 0·009947 ohm, at 13·5° Centigrade.

Field-magnet: Three forgings of hammered scrap iron, truly faced, and bolted together; section of limbs rectangular with corners slightly rounded. Stands on a zinc footstep, over a cast-iron bed-plate.

	Inch.	Centim.
Length of magnet limb	18	45·7
Breadth of limb (parallel to shaft)	$17\frac{1}{2}$	44·45
Thickness of limb	$8\frac{11}{16}$	22·1
Length of yoke	$24\frac{1}{4}$	61·6
Breadth of yoke	19	48·3
Depth of yoke	$9\frac{1}{8}$	23·2
Distance between centres of limbs ..	15	38·1
Diam. of bore of polar faces	$10\frac{13}{16}$	27·5
Depth of pole-pieces	9	25·4
Width of pole-piece at narrowest part ..	$8\frac{3}{8}$	21·3
Breadth of pole-pieces (parallel to shaft)	19	48·3
Width of gap between pole-pieces	5	12·7
Depth of edges of protruding horns ..	$\frac{5}{16}$	0·8
Thickness of gap-space (from iron to iron)	$\frac{19}{32}$	1·5
Thickness of zinc footstep	5	12·7
Angular breadth of polar face	129°	
Angular breadth of gap	51°	

The magnetizing coils are wound directly on the limbs, and consist of 11 layers on each limb of copper wire 0·100 inch, or 2·413 mm. diameter (No. 13 B.W.G.), having, therefore, cross section of 0·0071 sq. in. or 4·573 sq. mm., making 3260 convolutions in all; total length being approximately 15,000 feet, or 4570 metres. Resistance at 13·5° C. is 16·93 ohms.

Data for Calculating Reluctances in Magnetic Circuit.

1.—*Armature Core.*

l_1 taken as $5\frac{1}{8}$ inch or 13 cm.

A_1 taken as 125 sq. in. or 810 sq. cm.

2.—*Gap Space.*

l_2 is $\frac{19}{32}$ inch (= 0·59 inch), or 1·5 cm.

A_2 taken as 248 sq. in. or 1600 sq. cm. This allows $29\frac{1}{2}$ sq. inch, or 190 sq. cm. for fringing. The actual area of the polar face is $234\frac{1}{2}$ sq. in., or 1513 sq. cm.; and the corresponding area of 129° of surface of armature core is $218\frac{1}{2}$ sq. in., or 1410 sq. cm. Allow, for fringing, a margin all round equal to four-fifths of gap-space.

3.—*Magnet Limbs.*

l_3 is in total 36 inch, or 91·4 cm.

A_3 is taken at 152 sq. inch, or 980 sq. cm.

4.—*Yoke.*

l_4 is taken at $19\frac{1}{4}$ inch, 49 cm., estimated along quadrants.

A_4 is $173\frac{1}{2}$ sq. inch, or 1120 sq. cm.

5.—*Pole Pieces.*

l_5 is $4\frac{5}{16}$ inch, or 11 cm., estimated along curve.

A_5 is taken as $190\frac{1}{2}$ sq. inch, or 1230 sq. cm.; being mean area between section of limb and area of polar face.

Coefficient of leakage v was taken by Hopkinson as 1·32, but was probably nearer 1·4.

CALCULATIONS ABOUT THIS DYNAMO.

$C = 320$; $e = 105$; $n = \frac{750}{60} = 12·5$; $r_a = 0·01$; $r_s = 16·93$, whence $C_s = e \div r_s = 6·21$; $C_a = C + C_s = 326$; lost volts $= r_a \times C_a = 0·01 \times 326 = 3·26$; hence $E = e + r_a C_a = 108·26$ at full load. $Z = 80$.

$$N = \frac{E \times 100{,}000{,}000}{n Z} = \frac{108·26 \times 10}{12·5 \times 80} = 10{,}826{,}000.$$

Useful watts $= e \times C_a = 105 \times 320 = 33{,}600$.

2 A 2

Total watts $= E \times C_a$	$= 108 \cdot 26 \times 326 = 35{,}293$.
Electrical efficiency η	= useful watts $\div$ total watts.
,, ,,	$= 0 \cdot 952$, or $95 \cdot 2$ per cent.
Watts lost in armature	= lost volts $\times$ amperes;
,, ,, ,,	$= 3 \cdot 26 \times 326 = 1062 \cdot 76$.
Watts lost in magnets	= lost amperes $\times$ volts.
,, ,, ,,	$= 6 \times 105 = 630$.
Watts lost by hysteresis	$= 12 \cdot 5$ reversals per sec. in $0 \cdot 7$ cubic feet at 13,360 for B, see p. 140.
,, ,, ,,	$= 213$.

To find ampere-turns requisite to magnetize. By § 19 above;

$$SC = \frac{10}{4\pi} \times 10{,}826{,}000 \times \text{the total magnetic reluctance.}$$

This must be calculated from the 5 data of the magnetic circuit in separate parts, as on p. 146. First find values of B in separate parts according to leakage and cross-section, and from these values find corresponding values of μ by Table I., p. 126, or from Fig. 85.

1. Armature	$B_1 = 13{,}360$;	$\mu_1 = 1000$
3. Magnet limbs ..	$B_3 = 14{,}250$;	$\mu_3 = 796$
4. Yoke	$B_4 = 13{,}530$;	$\mu_4 = 895$
5. Pole-pieces ..	$B_5 = 11{,}450$;	$\mu_5 = 1566$

Inserting these values and those of the leakage coefficients, the magnetic reluctances come out:—

1. Armature	0·00001605
2. Gap-spaces	0·00187500
3. Magnet limbs	0·00015467
4. Yoke	0·00006845
5. Pole-pieces	0·00000151
Total magnetic reluctance ..	0·00211568

Whence

$$SC = \frac{10}{4\pi} \times 10{,}826{,}000 \times 0 \cdot 00211568$$
$$= 18226.$$

To this must be added the ampere-turns needed to compensate for demagnetizing action of armature. The number of armature con-

ductors between pole-tips is 11; but as the diameter of commutation is not quite at the pole-tips we take 9 as the demagnetizing belt. Multiplying this by half the armature current (163 amperes), and by the leakage coefficient (1·32) we get 1936 as the compensating number, making total requisite ampere-turns 20,162. Dividing this by the number of amperes of current allowed in the shunt-coil (6·21) gives 3214 as the requisite number of coils S on the field-magnet. The actual number wound on was 3260, which allows a margin for regulating.

EXAMPLE II.—THE KAPP DYNAMO.

Compound-Wound Dynamo with Drum Armature (*Over Type*).—Output 21 kilowatts; 200 amperes at 105 volts. Speed, 780 revolutions per minute. (Shown in Fig. 259 and Plates I., II. and III.) The *Armature*, which is described on p. 307, has the following dimensions:—

Core-disks, external diam.	$11\frac{1}{16}$ in.,	28·2 centim.
,, internal diam.	$6\frac{5}{16}$,,	19 ,,
Shaft diam.	$2\frac{13}{16}$,,	7·1 ,,
Radial depth of iron	$2\frac{3}{8}$,,	6 ,,
Gross length of core	16 ,,	40·6 ,,
Total thickness paper insulation	$2\frac{7}{8}$,,	7·3 ,,
Nett thickness of iron in core ..	$13\frac{1}{8}$,,	33·3 ,,
Nett cross section of iron, A_1 ..	62·5 sq. in.,	403 sq. cm.
Effective length, l_1	5·5 in.,	13·9 cm.

Particulars of conductors, &c.:

Number of conductors	120
Breadth	0·11 in., 0·279 centim.
Radial depth	0·208 ,, 0·528 ,,
Section of conductor..	0·046 sq. in., 0·297 sq. cm.
Total diam. of armature	$11\frac{5}{8}$ in., 29·6 centim.
Diam. of bore of poles	$11\frac{15}{16}$ in., 30·3 centim.
Resistance of armature (hot) ..	0·025 ohm.

The commutator has 60 segments insulated with mica.

The conductors are joined at the end of the armature by 120 semicircular connectors, each of which is 1·625 inch, or 4·1 cm.

deep and 0·05 inch or 0·127 cm. thick. These connectors are shown in Plate I.

The *Field-Magnet* consists of two limbs of wrought iron bolted to a cast-iron yoke (see Plate II).

	Inch.		Centim.
Total length of limbs	30	..	76·1
Breadth parallel to shaft	15	..	38·1
Thickness..	$5\frac{3}{4}$	..	14·5
Length of yoke	7	..	17·8
Breadth of yoke	17	..	43·2
Depth of yoke..	6	..	15·2
Distance between centres of limbs..	$12\frac{1}{4}$	..	31·2
Diam. of bore	$11\frac{15}{16}$	..	30·3
Depth of pole-pieces	12	..	30·5
Width of pole-piece at narrowest part	$3\frac{3}{16}$	..	8·0
Effective length of limbs l_3	23	..	58·4
Section of limbs A_3	105 sq. in.		677 sq. cm.

Angle subtended by polar face, 135°.
Coefficient of leakage, 1·3 at no load; 1·4 at full load.

The *shunt winding* consists of round copper wire of 0·065 inch or 0·165 cm. in diameter, covered by insulation which increases its diameter to 0·08 inch or 0·2 cm. There are eleven layers of this wire on each limb, and the two limbs are connected in series. Each layer contains 139 turns of wire, so that there are 3058 turns of wire on the shunt circuit.

The *series winding* consists of twenty-three turns of copper tape, whose section is 0·480″ × 0·130″ = 0·0624 sq. in. or 0·402 sq. cm. on each limb; and the two limbs are connected in parallel.

The resistance (hot) of the armature = 0·025 ohm.

The resistance (hot) of the shunt winding = 30·1 ohms.

The resistance (hot) of the series winding = 0·0079 ohm.

Two complete sets of calculations will now be made, the first of which applies to the machine when run at no load; and the second set when run at the full load of 200 amperes. In the first case, practically the whole E.M.F. generated in the armature is available at the terminals, and there are no armature reactions. In the second case there is a fall of E.M.F. over the resistance of the armature, and there are armature reactions which distort the field and produce demagnetization. To counterbalance these two effects is the function of the series winding.

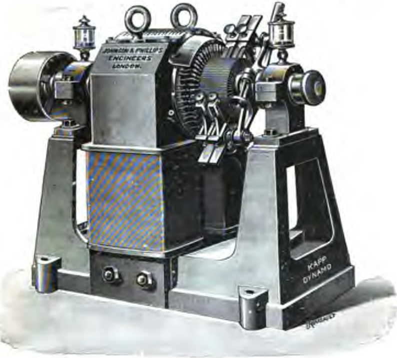


FIG. 259.—THE KAPP DYNAMO.

CALCULATIONS ON OPEN CIRCUIT.

The calculations in this case will be made throughout in inch measure.

ARMATURE.—The first operation is to find the number of lines of force that must be passing through the armature in order that 105 volts shall be generated in it.

Taking the formula

$$N = \frac{60 \times 10^8 \times E}{Z \times \text{revs. per min.}}$$

and substituting the values given above

$$N = \frac{60 \times 10^8 \times 105}{120 \times 780}$$
$$= 6,732,000 \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

This gives the number of lines passing through the armature. Dividing the above figure by the sectional area of the armature, we obtain the number of lines passing through each square inch of the armature; this is denoted by the letter B_1.

$$B_1 = \frac{6,732,000}{62 \cdot 5},$$
$$= 107,600 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

This gives the flux-density in the armature. On reference to the curve for wrought iron connecting μ_1 and B_1 (p. 125) we find that at this flux-density

$$\mu_1 = 210.$$

FIELD-MAGNETS.—*To find the number of lines passing through the field-magnets* it is only necessary to multiply the value (*a*) by the coefficient of leakage, which by experiment has been found to be about 1·3 in this class of machine.

$$N_2 = 6,732,000 \times 1 \cdot 3$$
$$= 8,750,000. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (d)$$

This value divided by the sectional areas of magnet-limbs and yoke respectively gives the flux-densities through them. Thus

$$B_2 = \frac{8,750,000}{105}$$
$$= 83,330 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (e)$$

This is the flux-density in the magnet-limbs, and on reference to Hopkinson's curve this corresponds to a

$$\mu_2 = 1230 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (f)$$

And in the yoke whose cross-section is 180 sq. in.

$$B_3 = \frac{8,732.000}{180}$$
$$= 48,610 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (g)$$

This is the flux-density in the yoke, and on reference to Hopkinson's curve for cast-iron, this corresponds to a permeability

$$\mu_3 = 125. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (h)$$

It will be noticed in these calculations that the pole-pieces are included in the magnet-limbs, which may be done without appreciable error in this type of machine.

MAGNETIC RELUCTANCE.—The next step is to find the ampere-turns per line needed for each part of the magnetic circuit, and this is done by substituting the values for the length, section and μ in the reluctance formula given on p. 350, viz. :—

$$\frac{l}{\mu\ A} \times 0 \cdot 3132.$$

So we get for the

$$\text{Armature} \qquad = \frac{5 \cdot 5 \times 0 \cdot 3132}{210 \times 62 \cdot 5}$$
$$= 0 \cdot 0001312 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (i)$$

$$\text{Magnet limbs} \qquad = \frac{2 \times 23 \times 0 \cdot 3132}{1230 \times 105}$$
$$= 0 \cdot 0001115 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (j)$$

$$\text{Yoke} \qquad = \frac{7 \times 0 \cdot 3132}{125 \times 180}$$
$$= 0 \cdot 00009743 \quad . \quad . \quad . \quad . \quad . \quad . \quad (k)$$

Air-gap.—The length of each air-gap is $\frac{7}{16}''$, but the area of the polar face must be found by calculation from the diameter of the magnet bore, the angle subtended by the polar face, and the breadth of the magnet, thus :—

$$\text{Area} = 15 \times \pi\, d \times \frac{135}{360}$$
$$= \frac{15 \times 3 \cdot 1416 \times 11\tfrac{15}{16} \times 135}{360}$$
$$= 211 \text{ square inches.}$$

Correction for Fringing.—To correct for fringing the following is a practical rule :—*Add to the actual area of the polar face an area whose length is equal to the periphery of the polar face, and whose breadth is equal to the length of the air-gap multiplied by* 0·8.

The periphery in the above case is $15'' + 14'' + 15'' + 14''$, and air-gap is $\frac{7}{16}''$. The correction for fringing is, therefore,

$$(15 + 14 + 15 + 14) \times \tfrac{7}{16} \times 0 \cdot 8 = 20 \cdot 3 \text{ square inches} \qquad (l)$$

The effective area of the polar face is, therefore,

$$211 + 20 \cdot 3 = 231 \cdot 3 \text{ square inches.}$$

$$\therefore \text{ reluctance of air-gaps} = \frac{2 \times \tfrac{7}{16} \times 0 \cdot 3132}{231 \cdot 3}$$
$$= 0 \cdot 001185 \quad . \quad . \quad . \quad . \quad (m)$$

Calculated Ampere-turns.

The next and final step is to find the number of ampere-turns, or magnetomotive-force, required to drive the given number of lines through the different portions of the magnetic circuit. This is found by multiplying the number of lines in any part by the magnetic reluctance of that part, thus:—

Armature (ampere-turns)	$S\,C = 6{,}732{,}000 \times 0 \cdot 0001312$	
	$= 883 \cdot 5$	(n)
Air-gaps	$S\,C = 6{,}732{,}000 \times 0 \cdot 001185$	
	$= 7{,}975$	(o)
Magnet limbs	$S\,C = 8{,}750{,}000 \times 0 \cdot 0001115$	
	$= 976 \cdot 1$	(q)
Yoke	$S\,C = 8{,}750{,}000 \times 0 \cdot 00009743$	
	$= 852 \cdot 5$	

Summary.

Ampere-turns required for	armature	=	883·5
,, ,,	air-gaps	=	7,975·0
,, ,,	magnet limbs	=	976·1
,, ,,	yoke	=	852·5
	Total		10,687·1

Our calculations, then, lead us to the conclusion that there must be 10687·1 ampere-turns wound on the shunt circuit, in order to drive sufficient lines through the armature to enable the dynamo to give 105 volts on open circuit at a speed of 780 revolutions per minute. Let us see how this result agrees with what actually exists on the machine.

Actual Ampere-turns.

The resistance of the shunt circuit is 30·1 ohms, and the pressure at its terminals of 105 volts. The current flowing through the shunt is, therefore,

$$C_s = \frac{105}{30 \cdot 1} = 3 \cdot 488 \text{ amperes} \quad . \quad . \quad . \quad (r)$$

and as there are 3058 turns of wire, the number of ampere-turns on the field-magnet is

$$S\,C = 3058 \times 3 \cdot 488 = 10{,}670, \quad . \quad . \quad . \quad (s)$$

which agrees almost exactly with the figure obtained by calculation.

Calculations at Full Load.

Since there is now a current of rather over 200 amperes flowing through the armature and series coils, there is necessarily a fall of pressure there, and as the terminal pressure must remain the same as before, the dynamo is called upon to generate a pressure equal to the sum of these two. The fall of pressure in the armature and series coils is obtained by multiplying their resistance by the current.

Thus $200\,(0 \cdot 025 + 0 \cdot 0079) = 6 \cdot 58$ volts.

Therefore, the total E.M.F. required to be generated by the dynamo is

$$\text{E.M.F.} = 105 + 6 \cdot 58 = 111 \cdot 58 \text{ volts.}$$

A similar set of calculations to the previous ones must now be made, assuming the new value of the E.M.F. thus

Lines through armature $\quad N' = \dfrac{60 \times 10^8 \times 111 \cdot 58}{780 \times 120}$

$= 7{,}153{,}000 \quad . \quad . \quad . \quad (a')$

Flux-density in armature $\quad B'_1 = \dfrac{7{,}153{,}000}{62 \cdot 5}$

$= 114{,}500 \quad . \quad . \quad . \quad . \quad . \quad (b')$

Corresponding to $\quad \mu'_1 = 100 \quad . \quad . \quad . \quad . \quad (c')$

Lines through field-magnets $\quad N'_2 = 7{,}153{,}000 \times 1 \cdot 3$

$= 9{,}298{,}000 \quad . \quad . \quad . \quad (d')$

Flux-density in limbs $\quad B'_2 = \dfrac{9{,}298{,}000}{105}$

$= 88{,}550 \quad . \quad . \quad . \quad . \quad . \quad (e')$

Corresponding to $\quad \mu'_2 = 950 \quad . \quad . \quad . \quad . \quad . \quad . \quad (f')$

Flux-density in yoke $\quad B'_3 = \dfrac{9{,}298{,}000}{180}$

$= 51{,}650 \quad . \quad . \quad . \quad . \quad . \quad (g')$

Corresponding to $\quad \mu'_3 = 95 \quad . \quad . \quad . \quad . \quad . \quad . \quad (h')$

Magnetic Reluctances.

Armature	$= \dfrac{5 \cdot 5 \times 0 \cdot 3132}{100 \times 62 \cdot 5}$
	$= 0 \cdot 0002756$ . . . (i')
Magnet-limbs	$= \dfrac{2 \times 23 \times 0 \cdot 3132}{950 \times 105}$
	$= 0 \cdot 0001444$ . . . (j')
Yoke	$= \dfrac{7 \times 0 \cdot 3132}{95 \times 180}$
	$= 0 \cdot 0001218$ . . . (k')
Air-gaps	$= 0 \cdot 001185$ (as before).

Calculated Ampere-turns.

Armature	$S\,C = 0 \cdot 0002756 \times 7{,}153{,}000$
	$= 1{,}972$ . . . . (n')
Air-gaps	$S\,C = 0 \cdot 0011850 \times 7{,}153{,}000$
	$= 8{,}474$ . . . . (o')
Magnet-limbs	$S\,C = 0 \cdot 0001444 \times 9{,}298{,}000$
	$= 1{,}343$ . . . . (p')
Yoke	$S\,C = 0 \cdot 0001218 \times 9{,}298{,}000$
	$= 1132$ . . . . (q')

Summary.

Ampere-turns	required for	armature	= 1,972
„	„	air-gaps	= 8,474
„	„	magnet-limbs	= 1,343
„	„	yoke	= 1,132
		Total	12,921

It is thus seen that 12,921 ampere-turns must be used instead of 10,687, in order to compensate for the lost volts in the armature. But even this increased number will not be sufficient to bring about the required result, owing to the demagnetizing effect which the armature exercises. It is found that there are eight conductors in the angle of lead at full load. This number multiplied by the current gives us 1600 demagnetizing ampere-turns. Now we see from (n') and (o') above that the magnetic potential between the pole pieces required to drive the flux through the armature and air-gaps is that of 10,446 ampere-turns. To this must be added a potential equivalent to 1600 ampere-turns to overcome the demagnetizing effect of the armature.

Now if the difference of magnetic potential between the poles is raised in this way the magnetic leakage will be raised proportionately. The coefficient of leakage will therefore be nearer 1·4 than 1·3. This means that the flux through the limbs and yoke is increased to about 10,000,000 lines. Taking the flux density in the limbs at 95,000 and in the yoke at 55,000, we have μ'_2 and μ'_3 reduced to about 750 and 75 respectively, and the ampere-turns required for these parts increased to 800 and 1500 respectively. Adding together the ampere-turns required to overcome the demagnetizing effect, and the reluctances of the air-gaps, armature, limbs and yoke, we get a total of 15,300.

Having now completed the calculations, let us set them down in a model schedule for use in future designs.

		$B_{\prime\prime}$	μ	Reluctance.	Ampere turns required.
Open Circuit.	Armature	107,600	210	0·0001312	883·5
	Air-gaps	29,000	1	0·001185	7,975
	Magnet-limbs ..	83,330	1,230	0·0001115	976
	Yoke	48,610	125	0·0000974	852·5
				Total	10,687
Full Load.	Armature	114,500	100	0·0002756	1,972
	Air-gaps	31,000	1	0·001185	8,474
	Magnet-limbs ..	95,000	750	0·000180	1,800
	Yoke	55,000	75	0·000150	1,500
					13,746
				Required to counteract demagnetization =	1,600
				Total	15,346

ACTUAL AMPERE-TURNS.

Let us compare this with what actually exists on the dynamo, and we find

Ampere-turns of shunt-winding	=	10,670 (as before).
" series winding (23 × 200)	=	4,600
Total ..		15,270

In practice the number of series ampere-turns cannot be foretold with the accuracy shown by the above figures. The usual course is to wind upon the dynamo the approximate number of series turns, and by running the machine find by experiment exactly how many ampere-turns are required to keep the volts at the desired amount at full load, and then the series winding is adjusted accordingly.

Example III. (already partly considered on pp. 340 to 344).

Design of a single-field compound-wound dynamo, with drum armature. Output 200 amperes at 55 volts at 1140 revolutions per minute. It is required to find the appropriate field-magnet.

Armature.—Built up of core-disks, separated by varnished manilla paper fixed by end-clamping upon a three-webbed sleeve of gun-metal. Shaft of Siemens steel. Commutator 36 parts. Conductors 72 all round periphery, in one layer. Hence at full load N must be about 4,170,000 lines; and at 90,000 lines to square inch this needs a nett cross-section of 45 square inches in core. Core disks, 7¼ inches exterior diameter, 4¼ inches interior diameter, in sufficient numbers to make up total nett length of 15 inches. Core disks are 28 mils (i. e. No. 22 S.W.G.) thick, so that about 536 of them are needed. Conductor, a stranded wire of 7 No. 13, overspun together with double cotton covering, and already lightly varnished with Scott's rubber varnish. Resistance of armature from brush to brush 0·007 ohm; length of armature winding, approximately 52 yards.

Field-magnets.—Horizontal limbs of best cast iron carefully annealed, lower one forming part of bed-plate casting. Section widening from lips so as to have section 194 square inches, and at parts furthest from armature 16½ inches wide by 11 inches deep, being bored out to receive the ends of the wrought-iron magnet core, which is a round forging, 10½ inches diameter, turned down at its ends to 10 inches diameter, where it is inserted into the horizontal pole-pieces. The finished machine generally resembles Fig. 102, p. 163, but is more massive in the field-magnets.

To find the proper length for this core, first make an approximate estimate of the needed number of ampere-turns, and thence calculate the quantity of windings and the proper length of core to receive the wire. Then design the magnetic circuit to be as compact as possible; and having so settled the sizes of the parts, calculate more exactly, as in the preceding example, the requisite number of ampere-turns to be provided on open circuit and at full load.

An example of a very detailed calculation of a dynamo is given by Wiener in the *Electrical World*, xxv. 662, June 8, 1895.

Experienced designers, accustomed to work at particular types of

machine, and with particular brands of iron, are able to simplify down their methods of calculation. They will, for example, settle by experience to design their machines to work at certain definite flux-densities in cores of armature and of magnets—hence at known permeabilities. They can then fix the number of ampere-turns needed per inch of length in each part of the magnetic circuit; and with the drawings before them can in a few moments determine the total ampere-turns needed for excitation.

USEFUL POINTS IN DESIGNING.

Peripheral Speeds.—The usual peripheral speeds appear to be from 2700 to 3000 feet per minute (*i. e.* 12 to 15 meters per second) for drums and cylindrical rings. For drum armatures destined for an output of K kilowatts, the suitable speed may be calculated by the formula $s = 3000\,K \div K + 1$. For large low-speed ring machines we may take $s = 2700\,K \div K + 5$. Esson maintains that 6000 feet per second can be safely attained in large machines. For discoidal rings and disk armatures, 3000 to 5000 feet per minute is usual. Ferranti's 15-foot armatures (Fig. 418) have peripheral speed of 5400 feet per second. Those alternators in which the field-magnet revolves may have higher peripheral speeds without risk of flying to pieces, some going over 7000 feet per minute. In the Niagara alternators the speed is 7854 feet per minute.

Core-disks.—These are usually from 25 to 50 mils in thickness, in continuous-current dynamos and motors. For alternate-current machines some makers use thinner stampings.

For rings, the ratio used in practice between the external and internal diameters is from 10 to 8 in small rings to 10 to 7 in large rings. In Brown's 4-pole rings (Fig. 276) the ratio is 10 to 7; in his 8-pole rings (Fig. 279) about 10 to 8. In Siemens' machines with internal magnets (Plate VIII.) the ratio is about 10 to 9. In machines with cast-iron magnets, the rings are usually made with a less radial depth of iron than in machines of wrought iron.

For bipolar drums, the usual ratio of external and internal diameters is 10 to 3. In Kapp's 2-pole machine (Plate I.) the ratio is 7 to 4. For multipolar drums greater internal

space is usual. In Brown's 6-pole drum (Fig. 240) the ratio is 5 to 3.

Proper Flux-density.—The limiting values to which it is found expedient in practice to push the flux-density have been several times alluded to. The values of B are here tabulated for convenience. As a rule, the higher flux-densities are admissible in the larger sizes only.[1] It seems to be recognised that the flux-density in the gap-space may be higher if the poles are of wrought iron or mild steel than if they are of cast iron.

Flux-density B = Lines per sq. cm.

Species of Dynamo.	In Armature.	In Gap-Space.	In Field-Magnet.	
			Wrought Iron.	Cast Iron.
Constant Potential Machines.				
2-Pole Drum	10,000 to 15,000	2,500 to 6,500	12,000 to 17,000	6,000 to 8,000
2-Pole Ring (long) ..	12,000 to 16,000	2,500 to 5,000	12,000 to 17,000	6,000 to 8,000
Multipolar Rings ..	10,000 to 15,000	3,000 to 8,500	12,000 to 17,000	6,000 to 8,000
Arc-Light Machines ..	17,000 to 20,000	3,000 to 7,000	17,000 to 20,000	6,000 to 10,000
Accumulator-charging Machines.	10,000 to 13,000	4,000 to 6,000	10,000 to 15,000	5,000 to 7,000
Alternators.				
Multipolar Ring ..	6,000 to 6,500	2,500 to 4,000	12,000 to 17,000	6,000 to 8,000
,, Drum ..	6,000 to 7,000	2,500 to 5,000	12,000 to 17,000	6,000 to 8,000
Coreless Disk	5,000	5,000	12,000	6,000

Specific Utilization of Copper.—Those machines in which the material is used to the greatest advantage will have the largest output in proportion to weight. Considering the

[1] See statistics by Wiener in *Electrical World*, xxiii. 713, 1894, where, however, teeth on cores are erroneously regarded as causing leakage through the armature.

copper in the armature only, the number of watts of output per lb. of copper will obviously be greater the denser the field and the higher the linear speed. Taking an average field of about 3000 lines per sq. cm., the watts per lb. of copper vary from below 100 in multipolar ring slow-speed machines to 500 or 600 in bipolar drum high-speed machines.

The length of wire to produce a given voltage at a given speed is a measure (inversely) of the density of magnetic field. The following are examples of 2-pole drum-wound dynamos:—Edison-Hopkinson, at 750 revolutions per minute, takes 19 inches per volt; Kapp, at 780 revolutions per minute, 35 inches per volt; Thomson-Houston arc-lighter, at 900 revolutions per minute, 148 inches per volt. With a peripheral speed of 3000 ft. per minute, in a field where the flux density is 6000, each inch of conductor generates about $\frac{1}{4}$ volt.

Size of Wire for Winding Armatures.—This will be further discussed under heading of permissible heating. Modern practice allows from 2000 to 3000 amperes per square inch, in conductors of ring-armatures, and even up to 4000 amperes per square inch in those with single-layer surface winding; but in the magnet coils only about 2000 amperes per square inch. Esson[1] has given a useful table of usual sizes of wire used in winding armatures to run at usual speeds, together with the number of layers of each that may be used for these currents without overheating.

Heating of Magnetic Coils.—All field-magnet coils are liable to heat, because even the purest copper offers resistance. If it be assumed that the thickness of the insulation is proportional to the thickness of the wire on which it is wound, it follows that the weight of copper in a coil filling a bobbin of given dimensions will be the same, whether a thick wire or a thin one be employed. Further, for a given volume to be filled with coils, the number of ohms of resistance of the coil will vary *directly as the square of the number of turns* in the coil. For if a coil wound with 100 turns of a given gauge be rewound with 200 turns of a wire having half the sectional area, the resistance of this new winding will obviously be four

[1] *Elec. Review*, xxvii. 546 (1891).

times as great as that of the original winding. Also, by a similar argument, it follows that the resistance of a coil of given volume will vary *inversely as the square of the sectional area* of the wire used. And as this area is proportional to the square of the diameter of the wire, it follows that the resistance is *inversely proportional to the fourth power of the diameter* of the wire used. (See also Appendix A.)

The amount of heat developed per second in a coil is the product of the resistance into the square of the strength of the current. To avoid waste, therefore, no unnecessary resistance should be introduced into any main-circuit coil. It is easy to show that with a coil of *given volume*, the heat-waste is the same for the same magnetizing power, no matter whether the coil consists of few windings of thick wire or many windings of thin wire. The heat per second is $C^2 r$, and the magnetizing power is $S C$; C being the current, r the resistance, and S the number of turns. But r varies as the square of S, if the volume occupied by the coils is constant. For suppose we double the number of coils, and halve the cross-sectional area of the wire, each foot of the thinner wire will offer twice as much resistance as before; and there are twice as many feet of wire. The resistance is quadrupled therefore. The heat is then proportional to $C^2 S^2$: and therefore the heat is proportional to the square of the magnetizing power. If, therefore, we apply the same magnetizing power by means of the coil, the heat-waste is the same, however the coil is wound. To magnetize the field-magnets of a dynamo to the same degree of intensity requires the same expenditure of electric energy, whether they are series wound or shunt wound, provided the volume is the same.

A simple way of looking at this matter is to regard the whole winding as consisting of one turn, there being a current, equal to the total ampere-turns, going only once round. Then this current divided by the total cross section of copper gives the current-density. We then see that for equal-sized bobbins (containing the same amount of copper) the magnetizing effect is simply proportional to the current density. Further, the power wasted per lb. of copper is proportional to the square of

the current-density. The following table gives the waste in watts for different current-densities in both inch and centimetre measure. The temperature of the coil is taken at 30° C., at which temperature the resistance of an inch cube of copper may be taken at $0·7 \times 10^{-6}$ ohm.

LOSS OF POWER IN COPPER CONDUCTORS AT DIFFERENT CURRENT-DENSITIES.

Current-Density.		Watts converted into Heat.		
Amperes per sq. in.	Amperes per sq. cm.	Per cubic in. of Copper.	Per cubic cm. of Copper.	Per lb. of Copper.
1000	155	0·7	0·042	2·17
1500	232	1·57	0·096	4·88
2000	310	2·8	0·171	8·71
2500	387	4·37	0·266	13·59
3000	465	6·3	0·384	19·59
3500	542	8·5	0·510	26·43
4000	620	11·2	0·683	34·83

If the *volume* of the coil (and the weight of copper in it) may be increased, then the heat-waste may be proportionally lessened. For example, suppose a shunt coil of resistance r has S turns; if we wind on another S turns in addition, the magnetizing power will remain nearly the same, though the current will be cut down to one-half owing to the doubling of the resistance; and the heat-loss will be halved, for $2\,r \times (\frac{1}{2}\,C)^2$ will be $\frac{1}{2}\,C^2\,r$.

It is assumed in the foregoing argument that we get double the number of turns on if we halve the sectional area of the copper wire. This is not quite true, because the thickness of the insulating covering bears a greater ratio to the diameter of the wire for wires of small gauge than for wires of large gauge. In designing dynamos, moreover, one ought to be guided by the question of economy, not by the accident of there being only a certain volume left for winding. If there is insufficient space round the cores to wind on the amount of

wire that economy dictates, new cores should be prepared having a sufficient length to receive the wire which is economically appropriate.

In order to calculate the diameter of the wire to be used in a shunt coil, we must first estimate the mean length of one turn. This can be done with considerable accuracy when the circumference of the iron limb and the approximate depth of winding are known. The diameter of the wire d must be such that the resistance ρ of one turn divided into the volts at the terminals of the shunt will give the total ampere-turns required or in symbols

$$\text{SC} = \frac{e}{\rho}.$$

If the bobbins are to be circular and of mean diameter δ we know that

$$\rho = \frac{\delta \times \pi}{d^2 \times \frac{1}{4}\pi} \times 1{\cdot}9 \times 10^{-6}.$$

Hence the diameter of the wire in centimetres will be

$$d = \sqrt{\frac{\text{SC} \times \delta \times 4 \times 1{\cdot}9}{e \times 10^6}}.$$

Example.—What thickness of copper wire must be used to wind a pair of shunt coils in order to obtain an aggregate of 18,930 ampere-turns, the winding on each cylindrical bobbin having a mean diameter of 17 centimetres, if the pressure at the terminals of the magnet is intended to be 100 volts (the two coils being in series with each other). *Answer:* 0·156 cm.

We have taken the resistance of a centimetre cube of copper to be $1{\cdot}9 \times 10^{-6}$ ohm. at 50° C. The figure will of course vary with the temperature of the coil. If the measurements are expressed in inches, we have

$$d_{\prime\prime} = \sqrt{\frac{\text{SC} \times \delta_{\prime\prime} \times 4 \times 0{\cdot}75}{e \times 10^6}}.$$

If no special limit of temperature-rise is prescribed, then the dominant consideration that governs the length of wire

used in winding is the amount of energy that may be wasted in magnetizing. If a temperature-limit is prescribed, then there must be provided a cooling-surface proportional to the energy that is wasted in the magnetizing coil. Experience shows that if the heating is not to exceed 20° to 25° (Cent.) above atmospheric temperature, at least 2½ square inches of external surface of coil must be allowed for each watt wasted by the coil's resistance. Or, conversely, if a bobbin has room for a coil of only a certain amount of surface, a winding must be chosen such that it will waste only one watt for each 2½ square inches of surface.

For shunt coils the length, and therefore the volume, is dictated solely by reasons of economy. It is usual to allow 25 to 40 yards per volt.

Permissible Heating and Surface of Emission.—In order that any coil may not overheat it must have sufficient surface relatively to the amount of heat developed in it by the current. In the Brush arc dynamo, 2 sq. inches of surface per watt lost are allowed in the field-magnets, and 0·9 sq. inches in the armatures; in the Thomson-Houston armature, 1·66 sq. inches. The relation between the heat developed, the surface of emission, and the resulting rise of temperature has been investigated by Forbes, Esson and others. Esson finds that from surfaces consisting of wire double cotton-covered and varnished heat will be emitted at the rate of $\frac{1}{355}$ of a watt[1] from 1 square centimetre if warmed 1° C. above the surrounding atmosphere. Within the range of ordinary heating it may be assumed that the rate of emission is proportional to the excess of temperature over the surrounding air.

[1] The *watt* is the unit of rate of expenditure of energy, and is equal to ten million ergs per second, or to $\frac{1}{746}$ of a horse-power. A current of one ampere, flowing through a resistance of one ohm, spends energy in heating at the rate of one watt. One watt is equivalent to 0·24 calories per second, of heat. That is to say, the heat developed in one second, by expenditure of energy at the rate of one watt, would suffice to warm one gramme of water through 0·24 (Centigrade) degrees. As 252 calories are equal to one British lb. (Fahrenheit) unit of heat, it follows that heat emitted at the rate of one watt would suffice to warm 3·4 pounds of water one degree Fahrenheit in one hour; or one British unit of heat equals 1050 watt-seconds.

Esson's rule, which appears to agree with the experience of various different makers, may then be stated

$$\theta^\circ \text{ C} = 355 \frac{w}{s};$$

where θ stands for the rise of temperature, w is the watts expended in heat in the coil, and s its surface in sq. cms. Or, if Fahrenheit degrees and sq. inches are used, the rule becomes

$$\theta^\circ \text{ F} = 100 \frac{w}{s}.$$

In using such rules, and calculating the watts developed in the coil (by multiplying the resistance by the square of the current), it must be remembered that the wire when warm has a higher resistance than when cold. A useful rule to take this into account is :—

To find resistance (hot) when resistance (cold) is known ; add to the known number of ohms 1 per cent. for every $2\frac{1}{2}$ Centigrade degrees, or for every $4\frac{1}{2}$ Fahrenheit degrees.

To find maximum permissible current, if the rise of temperature θ is prescribed as a limit.

$$\text{Max. permissible current} = \sqrt{\frac{\theta^\circ \text{ C} \times \text{sq. cm.}}{355 \times \text{resistance (hot)}}};$$

or

$$\text{Max. permissible current} = \sqrt{\frac{\theta^\circ \text{ F} \times \text{sq. inches}}{100 \times \text{resistance (hot)}}}.$$

EXAMPLE.—A coil has 450 sq. in. of surface, and a resistance (hot) of 15 ohms. It is required to know what is the largest current it can carry continuously without heating more than 30° F. above the surrounding air. Here the maximum current will be 3 amperes.

If we assume that a safe limit of temperature is 90° F. or 50° C.) higher than the surrounding air, then the largest current which may be used with a given electromagnet is expressed by the formula

$$\text{Highest permissible amperes} = 0{\cdot}95 \sqrt{\frac{s}{r}},$$

where s is the number of square inches of surface of the coils and r their resistance in ohms.

Similarly, for ***shunt coils*** we have

$$\text{Highest permissible volts} = 0{\cdot}95 \sqrt{s\,r}.$$

The magnetizing power of a shunt coil, supplied at a given number of volts of pressure, is independent of its length, and depends only on its gauge, but the longer the wire the *less* will be the heat waste. On the contrary, when the condition of supply is with a constant number of amperes of current, the magnetizing power of a coil is independent of the gauge of the wire, and depends only on its length; but the larger the gauge the less will be the heat waste.

In running armatures the rise of temperature is relatively less owing to circulation of air; but the cooling effect of running is less in those machines that have their armatures almost entirely covered by the polar surfaces than in those in which the armature is more exposed. Owing to the cooling effect of the air-currents while running, it is found that when a dynamo is stopped at the end of a long run, the surface temperature immediately rises above what it was when running, as the heat which is being conducted outwards from the hotter interior is not now so rapidly got rid of. In the Admiralty specifications it is laid down that after the end of a long run of six hours, no part of the machine shall at the end of one minute after stopping show a greater rise than 30° F. (= 16·6 C°.) above the surrounding air. This is needlessly low; for ordinary engine-room work a rise two or three times as great is perfectly safe. Kapp allows 1·5 sq. inch (= 9·7 sq. cm.) for each watt lost in the armature; and 2·5 sq. inches (= 16·2 sq. cm.) per watt in the field-magnet. Esson finds that on armatures running at ordinary speeds, there will be a rise of 35° C. if for every watt wasted in heating 1·13 sq. inch (= 7·3 sq. cm.) be allowed. The formula given above for field-magnets would show for the same rise a minimum surface of 1·5 sq. inch (= 9·7 sq. cm.) per watt. Esson finds an approximate rule for different speeds to be

$$\theta^\circ\,(\text{C.}) = \frac{55\,w}{s\,(1 + 0{\cdot}00018\,v)};$$

where s is given in square inches, and v is the peripheral velocity in feet per second. If these are given in square centimetres, and metres per second respectively, the rule becomes

$$\theta^\circ \text{ (C.)} = \frac{354\, w}{s\,(1 + 0{\cdot}0006\, v)}.$$

From an elaborate study by Messrs. A. H. and C. E. Timmermann,[1] it appears that the number of watts that can be radiated per square inch per degree (C.) of rise of temperature increases with the speed, being about 0·010 at zero speed, 0·018 at a speed of 1000 feet per minute, and 0·022 at 3000 feet per minute. For a temperature rise of 30° C. the number of square inches of radiating surface per watt is about 3·3 at zero speed, about 1·9 at 1000 feet per minute, and about 1·5 at 3000 feet per minute.

Some calculations about the greater heating of interior layers have been given by Mr. Joyce.[2]

The following rules are useful for calculating the windings for machines of same type, but of varying size, or output.

To reach the same limiting temperature with equal-sized bobbins wound with different-sized wire, the cross-section of the wire must vary as the current it is to carry; or in other words, the current density (amperes per square centimetre) must remain constant.

To raise to the same temperature two similarly shaped coils, differing in size only, and having the gauge of the wire in the same ratio (so that there are the same number of turns on the large coil as on the small one), the currents must be such that the squares of the currents are proportional to the cubes of the linear dimensions.

Similar iron cores, similarly wound with lengths of wire proportional to the squares of their linear dimensions, will when excited with equal currents, produce equal magnetic forces at points similarly situated with respect to them. (Lord Kelvin, *Phil. Trans.*, 1856.)

[1] *Trans. Amer. Inst. Electr. Engineers*, x. 1893.
[2] *Journ. Inst. Electr. Engineers*, xix. 248, 1890.

Similar machines, if magnetized to an equal degree of saturation, must have ampere-turns proportional to the linear dimensions.

If two machines are to give same electromotive-force, the diameter of the wire of the coils must vary as the linear dimensions.

If, in altering the field-magnets of a machine of any given capacity, the lengths of the several portions of the magnetic circuit remain the same, but the several areas are altered, then the wire for rewinding must have its cross-sectional area altered in proportion to the periphery of the section of the cores.

The resistance of a coil, the volume of which is known, and which is wound with (round) copper wire of diameter d millimetres, enlarged by insulation to a diameter of D millimetres, can be calculated by the following rule, which is based on the assumption that the partial bedding of the convolutions allows of 10 per cent. more wires being got in than would be the case if they were exactly wound in square order. This figure can only be approximate, as the amount of bedding varies somewhat with the relative thickness and pliability of the coating of insulating materials, as well as with the gauge of the wire. If v be the volume in cubic centimetres, the resistance r of the coil in ohms (cold) would be

$$r = 0{\cdot}0244 \frac{v}{\mathrm{D}^2 d^2}.$$

If v be expressed in cubic inches, and D and d in mils (1 mil = ·001 inch), then the approximate formula becomes

$$r = 960{,}700 \frac{v}{\mathrm{D}^2 d^2}.$$

Length and Diameter of Armatures.

Various rules have been given for the ratio between the length, L, of an armature-core and its diameter, d, embodying the results of practice.

In the case of 2-pole dynamos the usual dimensions for

ring armatures vary from L = ½ d to L = 1½ d; L = d being frequent. For bipolar drums L = 2 d is frequent, though the values L = 1½ d and L = 3 d are also found. In the Edison standard bipolar machines L varies from 1·85 to 1·9 d in the sizes from 1 to 50 kilowatts. For multipolar machines the diameter is usually greater than the length. In Brown's 6-pole drum, Plate VII., and Fig. 240, d = 2 L nearly.

SECTION OF FIELD-MAGNETS.

Comparison of the machines of various makers shows that for ring machines the usual practice is to allow for magnet-cores of ring machines a cross-section 1·66 times that of the armature-core, if of wrought iron or mild cast steel; or 3 times, if the magnet-core is of cast iron. For the magnet-cores of drum machines the usual figures are 1·25 and 2·3.

The question sometimes arises, what is the best *shape* of section to give to magnet-cores. This point is readily answered by considering the geometrical fact that of all possible forms enclosing equal area the one with least periphery is the circle. For facilitating comparison, the following table exhibits the relative lengths of wire required to wind round various forms of section enclosing equal area; the area of the simple circular form being taken as unity, and allowance made for thickness of winding:—

Circle	3·54
Square	4·00
Rectangle, 2 : 1	4·24
Rectangle, 3 : 1	4·62
Rectangle, 10 : 1	6·91
Oblong made of one square between two semicircles	3·76
Oblong made of two squares between two semicircles	4·28
Two circles side by side	4·997
Two circles, but wire wound round both together ..	4·10
Three circles ,, ,, ,, ,, each separately	6·13
Four circles ,, ,, ,, ,, ,, ,,	7·09

Symmetry of Field-magnets.—It was pointed out on p. 167, that in 2-pole single-circuit field-magnets the field is unsym-

metrical, being much stronger between the inner horns than between the outer horns of the pole-pieces, if the poles are shaped away as in Fig. 100, No. 23. Such shaping produces several evil results. Firstly, the armature is attracted downwards as a whole (see p. 327); secondly, the armature, if ring-wound, will be electrically out of balance, owing to the unequal magnetic fields at opposite ends of a diameter; thirdly, the neutral points for non-sparking will not be at opposite ends of a diameter.

Effect of Widening the Gap-space.—The effect of widening the gap-space is in every case to necessitate more ampere-turns of excitation. It also has some other results. It slightly increases the leakage coefficient v. It enables thicker copper

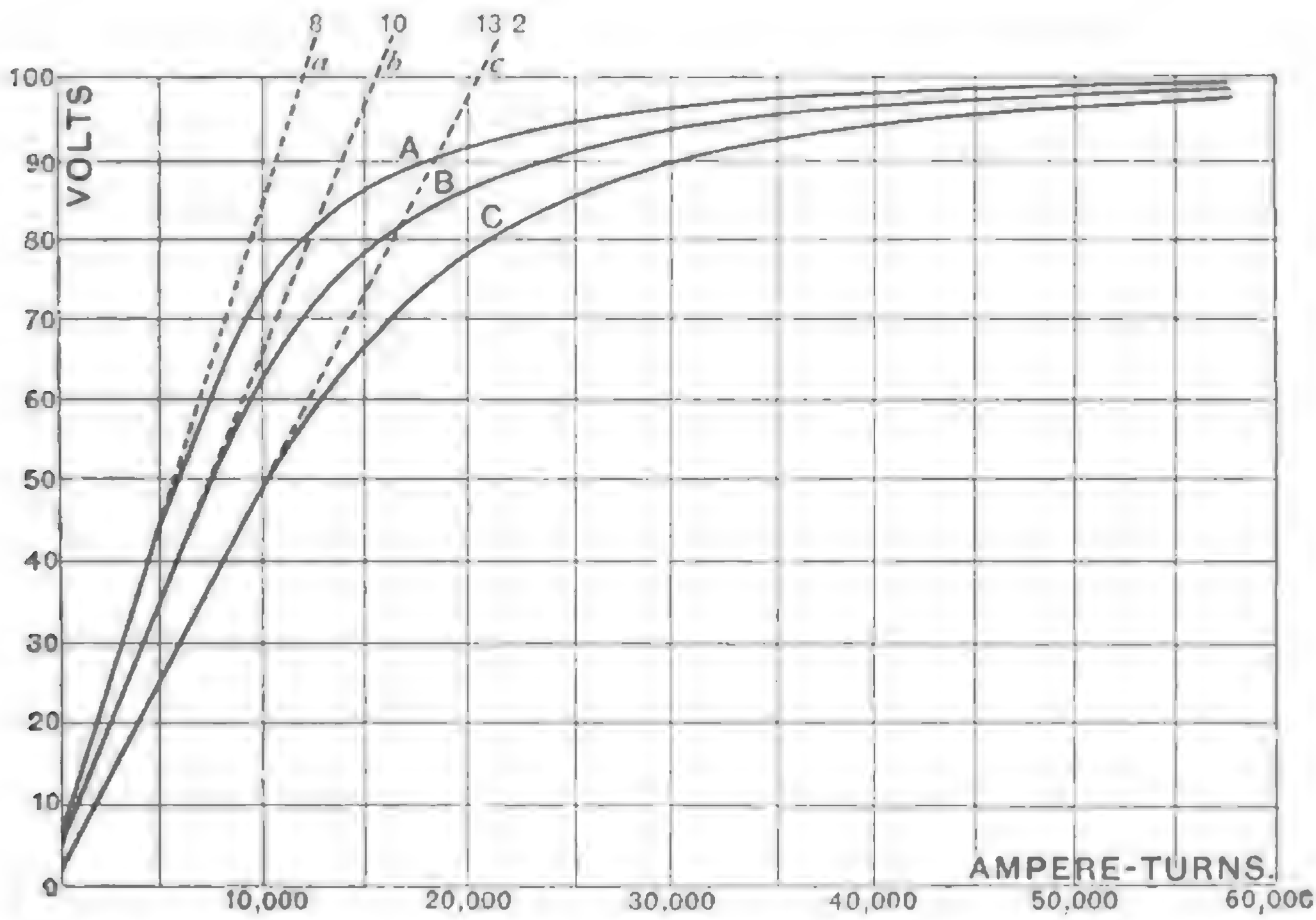


FIG. 260.—EXCITATION NEEDED WITH DIFFERENT GAP-SPACES.

conductors to be wound on the armature, diminishing its internal resistance; and, if the armature has not been loaded beyond the safe point of sparklessness, increases the output of the machine. It has the further not unimportant result of increasing the reluctance in the path of the cross-magnetizing

magnetomotive-forces, and diminishes their prejudicial action. Some ideas as to the first of these effects may be gathered from considering the curves given by Arnoux, in Fig. 260, showing the result of widening a gap-space from 8 to 10, and then to 13·2 millimetres. The initial slopes of the curves are given by lines whose tangents are inversely proportional to the gaps. It will be noted that in their upper part the three lines approach one another.

Interference of Armature Field.

As explained in Chapter IV., p. 71, the armature-current tends to cross-magnetize, and, if the brushes have a forward lead (or in a motor a backward lead) tends also to demagnetize the field. We saw on p. 80 that the position of the

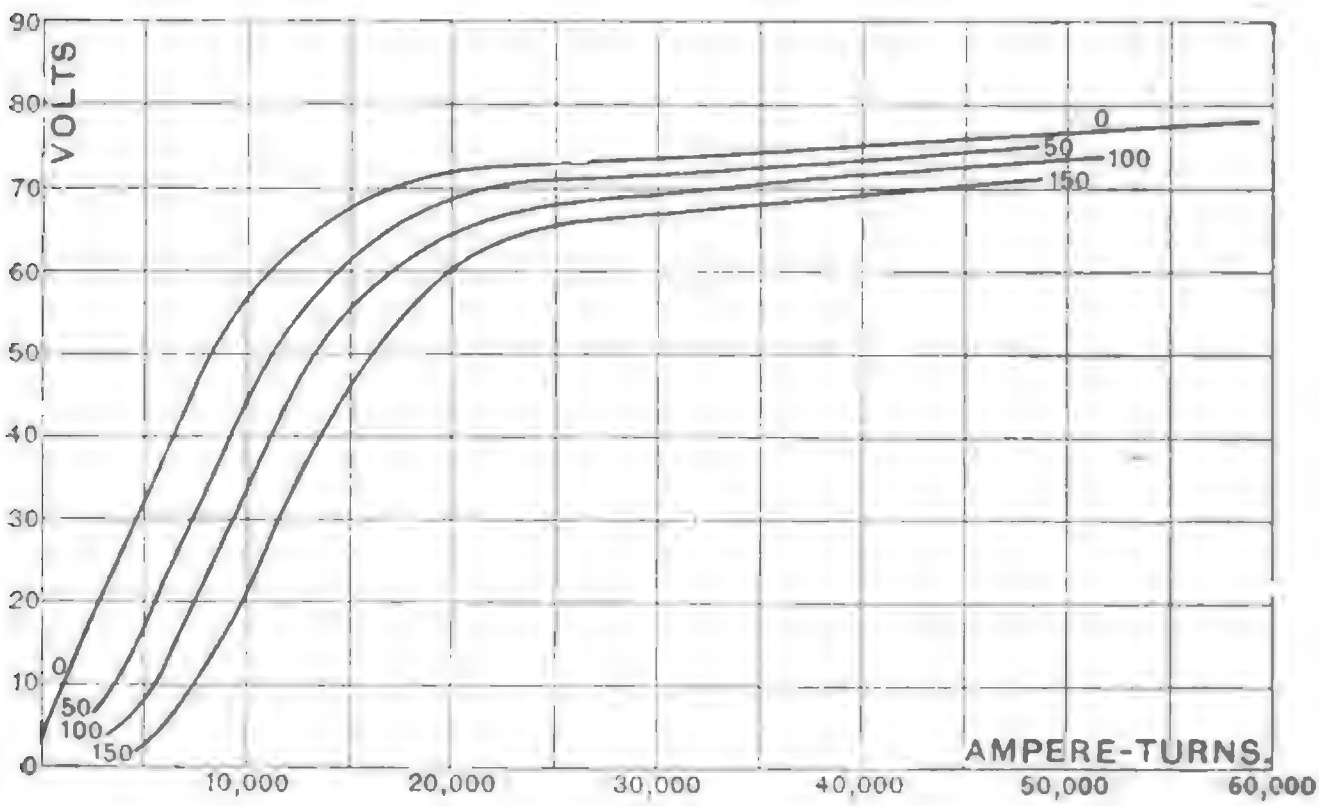


Fig. 261.—Load-Curves of a Dynamo.

neutral point for non-sparking is affected by this interference; and on p. 353 we learned how to compensate the demagnetizing effect. We have now to consider the matter further from the point of view of dynamo design.

In the first place, let us examine the behaviour of some

existing dynamo, by observing the relation between its voltage and the amount of excitation, at some constant speed, under varying conditions of load. Let the lead given to the brushes be varied as required to fulfil the condition of sparklessness. First let a curve be found with zero armature current; then with a 50-ampere load, then with 100 amperes, and so forth. The experiments should be made in each case by beginning with the highest excitation (and smallest angle of lead) and gradually diminishing the excitation (and increasing the lead) until a sparkless position can no longer be found for the brushes. This dynamo[1] was intended for a normal output of 150 amperes at 70 volts. It will be found that in each case, the smaller the load the more may the excitation of the field be diminished before the state of things is reached that no neutral point can be found. In other words, there will always be some definite relation between the ampere-turns on the armature, and those on the field-magnet which fixes the working limit of sparklessness. We shall presently enquire into this relation. For the present it may be remarked that these load-curves[2] give us much information as to the necessary windings of the field-magnet, how many ampere-turns must be contributed on open circuit by the shunt coil, and how many compensating ampere-turns must be added by the series coil in order to keep up the voltage.

Limits of Load and Non-sparking Point.—Two things limit the output of a dynamo: the heating of its armature conductors, and sparking at the brushes. Given a dynamo, if by widening the gap a little and rewinding its armature with copper wire of double cross-section, we reduce its resistance to one-half, we may then take from it nearly a double current with no more heating than before, provided it still does not spark. Such a reconstituted machine would clearly cost less than two of the previous pattern. But the limit of such an augmentation of the output by increasing the ampere-turns on

[1] See Arnoux in *Bull. de la Soc. Int. des Électriciens*, vi. 61, 1889.

[2] For other examples of load-curves see Esson in *Journal Instit. Electrical Engineers*, xix. 152, 1890; and Kapp, in *Proc. Instit. Civil Engineers*, Feb. 1889.

the armature is reached very soon; for the cross-magnetizing tendency is doubled, and the lead increased, and the demagnetizing tendency more than doubled by doubling the ampere-turns of the armature. These perturbing effects may be all included under the general name of *interference* used in the previous paragraph: they have been investigated more or less fully by Hopkinson,[1] and more completely by Swinburne,[2] and by Esson.[3]

It has been pointed out on p. 79, that because the windings of the armature possess self-induction, the reversal of the current in them in the act of commutation as they pass the brush requires the presence of an impressed electromotive-force; and that this is accomplished by giving the brush a lead (forward in a dynamo, backward in a motor) so that that section in which the current is to be reversed is at that time passing through the fringe of the magnetic field. The stronger the current to be reversed, the stronger is the field necessary for sparkless reversal. But the field under the "trailing" horn of a pole-piece (or in a motor, the "leading" horn), near which commutation must take place is, as we have seen (Figs. 62 and 66), weakened by the interference of the armature. Now the cross-magnetizing action of the armature tends to send magnetic lines up (see usual diagram Fig. 61, p. 73) both sides of the ring core, which tend to cross the gaps and return through the masses of the pole-pieces; the strongest cross-magnetizing force in the gaps being under the tips of the polar horns. This cross action opposes the normal flux of magnetic lines at the top right and bottom left corners (of Fig. 63), and helps it at the other two. The cross-magnetizing magnetomotive-force under the pole-tips (assuming the gaps alone to offer any appreciable reluctance) is equal to $\frac{4}{10}\pi$ times the ampere-turns of all the conductors that lie in the

[1] *Philosophical Transactions*, 1886, pt. i. p. 331; and *Electrician*, xviii., Dec. 1886.

[2] *Journal Instit. Electrical Engineers*, xv. p. 540, 1886; and xix. pp. 90 and 265, 1890.

[3] *Ib.*, xix. p. 118, 1890; and xx. p. 265, 1891; also *Electrical World*, xv. 213, 1890; see also *Electrical Review*, series of articles on Synthetic Study of Dynamos, 1890.

gaps, or within the angle of polar span ψ. Using the usual symbols—Z for the number of conductors around the armature, and C_a for total armature current—we have for the total ampere-turns on the armature $\frac{1}{2} Z \times \frac{1}{2} C_a$, of which $\psi \div 180°$ are effective, and of which the half may be taken as the part operative in either place where the cross-circuit crosses a gap. If ψ is taken at 120°, the cross-force under the tip will be

$$\tfrac{1}{2} Z \times \tfrac{1}{2} C_a \times \tfrac{1}{2} \times \tfrac{4}{10} \pi \times \tfrac{120}{180} = C_a Z \times 0 \cdot 104 ;$$

or equals the ampere-turns[1] on the armature multiplied by 0·416. Now let us see what number of ampere-turns on the armature would produce a cross-force in the gap just exactly balancing the normal magnetizing force there, so as to neutralize the field under the pole-tip. In that case sparkless reversal would be impossible, and so we should have ascertained the limit of load. Now the difference of magnetic potential in the gap (or that part of the magnetomotive-force that is spent therein) is equal to the product of the magnetic reluctance of the gap into the flux across it. If l_2 be the length across the gap and A_2 the polar area, the reluctance of the gap is $l_2 \div A_2$, and the magnetic potential-difference in it is $= N\, l_2 \div A_2$. Now call the length of the armature core or of the pole-face, parallel to the axis, L; the breadth of the pole-face measured along the curve from tip to tip b; the radial depth of the core r; and its sectional area A_1. We may assume that in the core the magnetization is pushed to $B = 17{,}000$. Then we have the following relations :—

$$N = 17{,}000\, A_1 \,;\; A_1 = r\, L \,;\; A_2 = b\, L.$$

[1] This term is here used precisely as for any electromagnet. In bipolar drum-armatures it is half the armature current multiplied by half the number of external conductors. In multipolar machines (wound wi h parallel grouping) it is equal to total current multiplied by total number of conductors and divided by the square of the number of poles. In Esson's paper of 1890 (*Journal I.E.E.*, xix. 143), the term ampere-turns was used in a different sense, namely, as the product of the total number of conductors into the current carried by each. This is the same thing to which in his paper of 1891 (*Journal I.E.E.*, xx. 266) he gave the not very apposite name of "volume," but which would have been better described as the total circulation of armature current. The name used hereafter for this quantity is the *circumflux*. For 2-pole machines the circumflux is twice the ampere-turns; for 4-pole machines, four times, &c.

Substituting these in the preceding expression, and cancelling out L, we get

Magnetic potential in gap = $17{,}000 \times r \times l_2 \div b$.

Equating this to the cross-force, we get

$$\frac{C_a Z}{4} = \frac{40900\, r l_2}{b}.$$

For some purposes it is more convenient—particularly in relation to multipolar machines—to consider not the ampere-turns of the armature, but the effective circulation of current as reckoned by multiplying together the number of armature conductors and the current carried by each independently of its direction. This quantity, here denoted by the symbol Q, we shall call the *circumflux*.[1] It is equal to the product of the whole armature current, into the whole number of armature conductors, divided by the number of poles. For a 2-pole dynamo we then have as the limiting load on the armature

$$Q = \frac{C_a Z}{2} = \frac{81800\, r l_2}{b}$$

Esson[2] gives the result of observation of a number of modern dynamos by different makers, and found the actual numerical coefficient to vary from 61,265 to 95,905 for ring machines, with a mean of 85,000, differing little from the theoretical 81,800 given above.

From the foregoing it appears that the maximum load which an armature can carry, within the limit of sparklessness, is directly proportional to the radial depth of core, and to the length of the gap, but inversely proportional to the breadth of the polar span. If, therefore, taking an existing machine whose load is just within the spark limit, we wish to make it carry a heavier load (or more copper on the armature) we may do so either by increasing the radial depth of the core-disks, or by increasing the gap-space (whether wanted for copper

[1] Called by Esson at one time the "ampere-turns," and later the "volume" of the armature current. See preceding footnote.

[2] *Journal I.E.E.*, xx. 142, 1890.

and clearance or not), or lastly, by diminishing the breadth of span of the polar faces. The first of these causes means a new armature; the second requires the pole-faces to be bored out afresh, and also means some (not large) addition to the magnetizing power of the field-magnet; the third has the effect of concentrating the magnetic flux, therefore, lowering slightly the permeability, and necessitating either a slightly higher speed or a slight increase in the magnetizing power.

The circumflux or polar circulation of armature current permissible for an armature of given diameter may be given in terms of the diameter by assuming (for ring 2-pole armatures) that $b = 1{\cdot}05\,d$; $r = 0{\cdot}1\,d$; and $l_2 = 0{\cdot}05\,d$.

Substituting these values, we get

$$Q = 390\,d.$$

Esson takes $400\,d$ (centimetres) as the limiting value of Q, for rings, and $600\,d$ as the value for drums. Kapp allows 1000 ampere-turns (or 2000 circumflux in case of 2-pole machine) for each inch of diameter above 12 inches, as a safe load.

We are now ready to consider the safe output (watts) of a dynamo in terms of its dimensions.

The gross output of a bipolar dynamo is—

$$W = E\,C_a = n\,N\,Z\,C_a \div 10^8; \qquad \text{(see p. 170)}$$

or for a multipolar dynamo—

$$W = n\,N\,\frac{CS}{p} \div 10^8;$$

where p stands for the number of *pairs* of poles: so that the value of Q, the circumflux of armature current, will be $Z\,C_a \div 2p$; whence

$$W = 2\,n\,N \times Q \div 10^8. \qquad [\ a\ ]$$

Now assume (as fair average of actual cases) that pole-pieces together cover $\frac{7}{10}$ of circumference (or $2{\cdot}2 \times d$), and that the value of B in the gap is 5000. Then, if L is length of armature core (cms.), the working area of the armature

through which magnetic lines go in or out $= 2 \cdot 2 \times d \times L$; whence area of any one polar part is $2 \cdot 2 d \times L \div 2p$; and the flux of magnetic lines through any one pole will be 5000 times this; or for the total flux through the $2p$ poles will be

$$N = p \times 5000 \times 2 \cdot 2 d \times L \div 2p = 5500 d \times L.$$

Inserting this value we have—

$$W = 11000 \times d + L \times n \times Q \div 10^8 \qquad [\,\beta\,]$$

But, according to Esson, as above, $Q = 400 d$ for rings or $600 d$ for drums as the safe loads. Inserting these values we get[1]—

$$\left.\begin{matrix} \text{for rings} & W = d^2 L n \times 0 \cdot 044 \\ \text{for drums} & W = d^2 L n \times 0 \cdot 066 \end{matrix}\right\} \qquad [\,\gamma\,]$$

Now $d^2 L$ is proportional to the volume of the armature core. Hence we conclude that the output is proportional to volume and to speed, and is independent of the number of poles and of the grouping of the armature conductors. Kapp finds it (for equal surface temperature) to increase as the $3\frac{1}{2}$ power of the diameter. This is a slightly higher proportion than the volume, probably because of the somewhat higher peripheral speeds admissible for large armatures.

Devices for Compensating Armature Reaction.

As the output of a dynamo is limited both by heating and by sparking, the designer must consider very closely how the latter can be abolished. There are many cases in which a dynamo or motor might be called upon to give double its normal output for a few minutes. Double output means quadruple heating, which if continued for only a short time may do no harm; whereas if sparking were to continue at the commutator for an equal time serious damage might be done. It is therefore important to so design machines that even

[1] Esson, taking slightly greater width of pole-pieces, gets 0·048 and 0·072 as the respective co-efficients. Snell (*Journal I.E.E.*, xx. p. 197) finds his machines give as their co-efficients, when translated into centimetres and seconds to correspond, 0·0375 and 0·056 respectively.

with double load they will not spark at the commutator. We have seen how the limit at which sparking begins depends upon the armature reaction, interfering with the field in the neighbourhood of the pole-tips, where it is needed for procuring sparkless reversal.

Consider first the theory[1] of armature interference. Draw any closed curve A B C A along the magnetic circuit (Fig. 262) so that it passes through the magnetizing coils. The line integral of the magnetizing forces along this line will be equal (see p. 118) to $0 \cdot 4 \pi$ times the ampere-turns in the coils. There will be an equal magnetomotive-force around the closed curve D E F D, though the resulting flux along this path may be less, owing to the greater reluctance. Similarly if the brushes are advanced with an angular lead λ, the number of conductors in the demagnetizing zone (see p. 85) will be a fraction $2 \lambda \div \pi$ of the whole number Z on the armature, and as each carries half the current, the demagnetizing ampere-turns (for drum-winding) will be

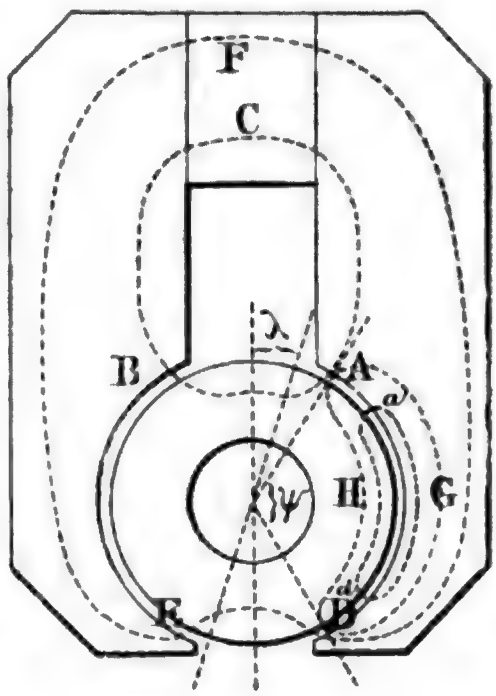


FIG. 262.
ARMATURE INTERFERENCE.

$$\tfrac{1}{2} C_a \times \tfrac{1}{2} Z \times 2 \lambda \div \pi = \lambda C_a Z \div 2 \pi,$$

and the demagnetizing magnetomotive-force will be $0 \cdot 2 \lambda C_a Z$. Further, the tendency to cross-magnetize may be calculated by considering the closed curve H A G D H drawn through the pole-tips of one pole-piece. If the angle of polar span be called ψ, the number of conductors enclosed by this curve will be $\psi Z / 2 \pi$, and the line-integral of the cross-magnetizing forces will be $0 \cdot 4 \pi \times \tfrac{1}{2} C_a \times \psi Z / 2 \pi, = 0 \cdot 1 \psi C_a Z$. As the reluctance in the parts of this path which pass through iron is

[1] Drs. J. and E. Hopkinson, *Phil. Trans.*, 1886; also reprint of Hopkinson's *Original Papers*, 1893, 105.

negligible, we may regard the whole of this as expended on the gaps at A and D; and it will be seen that the difference of magnetic potential at the gap A will be diminished, and that at D increased, by half this amount. Since any smaller closed curve, as at *a d*, encloses fewer conductors, it will produce a proportionately smaller distorting effect. The minimum field required for reversal in the neighbourhood of the pole-tip depends both on the current to be reversed, on the self-induction of the "section," and on the time occupied in the act of commutation. The cross-force which tends to diminish the field at the region A must not be suffered to reduce the field below the necessary minimum. It will be noted that the demagnetizing reaction (which is proportional to λ) tends to weaken the field in general, while the cross-magnetizing reaction tends (which is proportional to ψ) to weaken the field under the leading pole-tips, and to strengthen it under the trailing tips. In order that we may be able to reverse sparklessly very great currents, we must have the impressed field so strong that at least the minimum field remains at the pole-tip in spite of both these reactions. Seeing, then, that the cross-field is responsible for the distortion which makes sparkless collection difficult, it remains to consider the remedies. These may be classified under two heads—those applied to the magnets, and those applied to the armature. The former class may again be sub-classified; for in dealing with the cross-field we have two courses open, either to increase the reluctance in the path or to introduce a compensating counter cross magnetomotive-force.

Cross-Reluctance Remedies.—Any gap introduced across the closed path H A G D H of the cross forces will diminish the cross-field; hence merely widening the clearance of the armature will to some extent help; but then more winding will be wanted on the magnet-cores. The polar mass behind the face may be nearly divided by a "V" groove; as is readily done in the case of magnets of the Manchester type (No. 24, Fig. 101) and other forms having double magnetic circuits (as No. 8, Fig. 100 and Fig. 109) by judicious thinning, or by actual separation, as in No. 27, Fig. 101, between the right

and left-hand halves, and so throttle the cross-flux of magnetic lines. To prevent weakening of the structure a thin web is

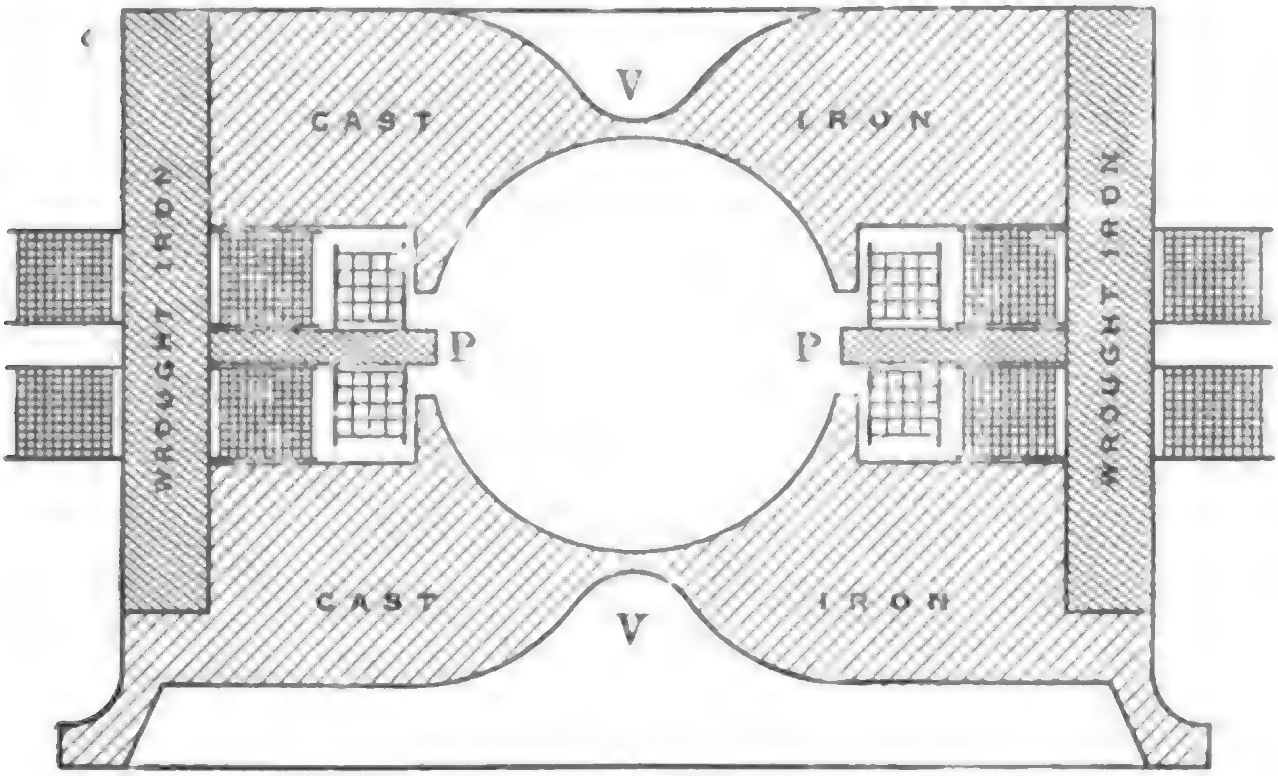


FIG. 263.—MAGNET WITH V-GAPS AND COMPENSATING POLES.

left in the casting, as in Fig. 263. Another suggestion, made by the author of this work some years ago, was to construct the field-magnets of pieces of iron, with longitudinal gaps, as in Fig. 264.

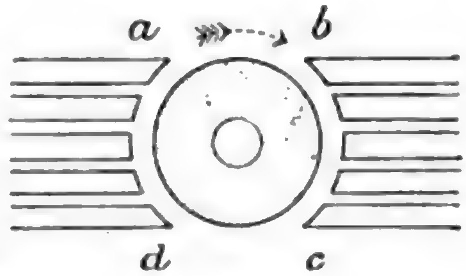


FIG. 264.

Cross-Compounding Remedies.—Elihu Thomson proposed to place a compounding coil on a separate frame surrounding the armature, and to tilt it in a direction counter to the rotation so as partially to counteract the cross force. Swinburne[1] suggested that a small auxiliary coil (in series) should be wound upon the tip of the pole, as in Fig. 265*a*, to maintain a reversing field at that point. Mather,[2] Housman,[3] and Swinburne[4] have all advocated the use of auxiliary poles at

[1] *Journ. Soc. Teleg. Engineers*, xv. 542, 1886.

[2] *La Lumière Électrique*, xix. 404, 1885.

[3] *Journ. Inst. El. Engineers*, xx. 299, 1891.

[4] See Swinburne (*Journal I.E.E.*, xxx. 105, 1890); and Housman (*ib.*, xx. 299, 1891), who maintains that if $B = 7000$ under the pole-piece, the auxiliary field for reversing must be at least $= 3000$.

right-angles to the main poles (as in Fig. 263), wound with main circuit coils to counteract the armature force. The

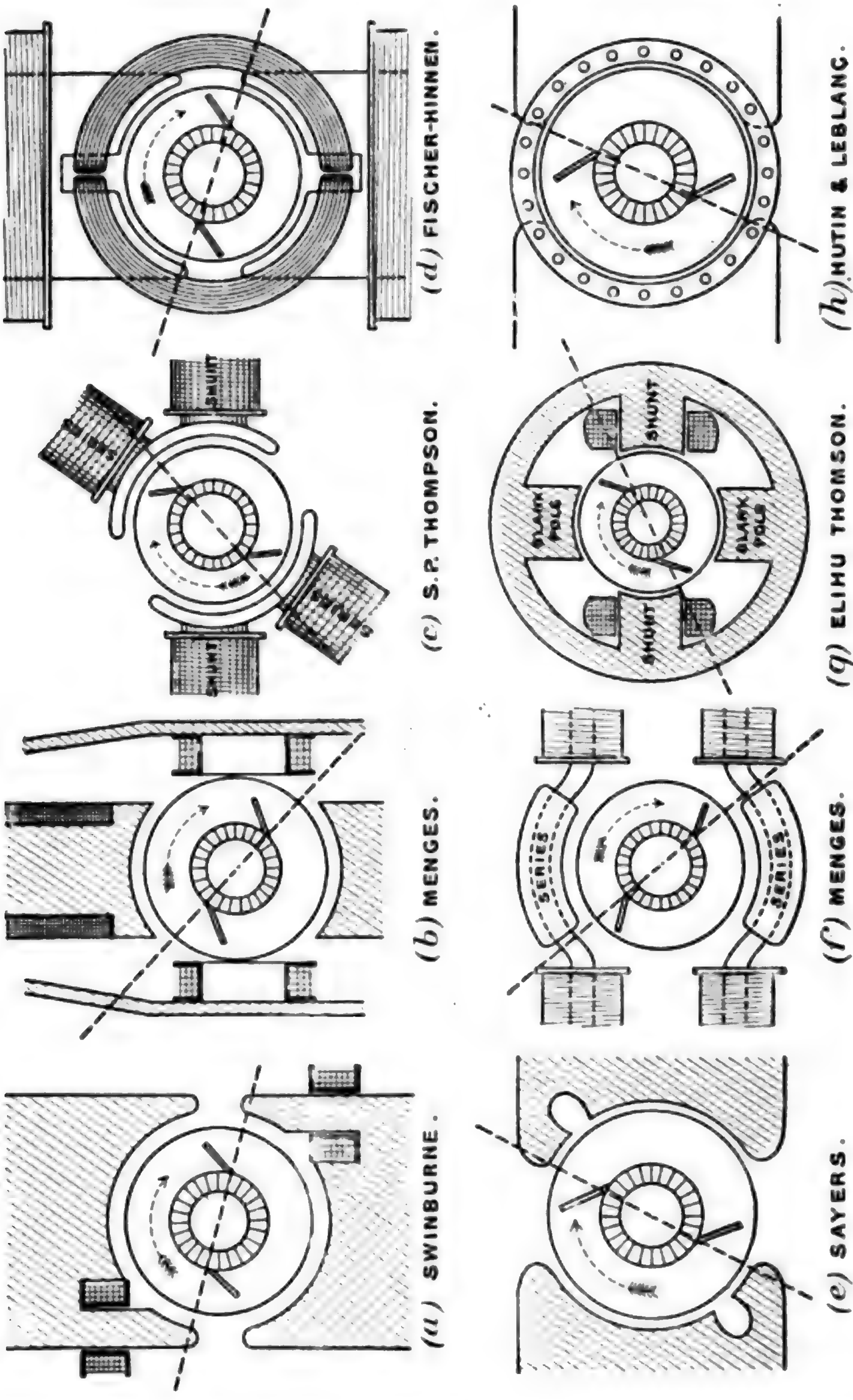


Fig. 265.—Various Devices for Sparkless Collection of Current.

author of this treatise suggested a sort of compound winding having series and shunt poles at different angles (Fig. 265*c*)

so that as the armature reaction tended to shift the field forward, the field should automatically shift itself back. Menges,[1] in 1884, proposed a cross-compound winding having the auxiliary series coils set to produce a field at right angles (Fig. 265*b*) to the ordinary field. He also suggested winding series coils around the polar parts of a machine with double magnetic circuit, as in Fig. 265*f*. Fischer-Hinnen[2] winds these coils in a notch at the centre of the pole-face (Fig. 265 *d*), a construction which independently occurred to Prof. Forbes, to Mr. Mordey, and the author.

Prof. Elihu Thomson[3] has lately proposed another solution (Fig. 265 *g*), in which, by the use of auxiliary unwound poles presented, at right-angles, to the armature, he leads off the

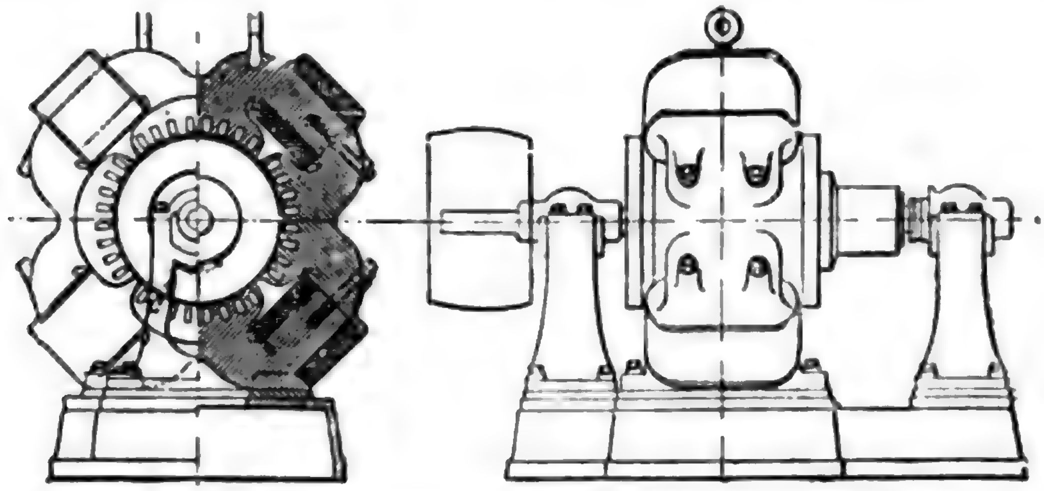


FIG. 266.—RYAN'S DYNAMO, WITH CROSS-COMPOUND COILS.

cross-flux into the back of the wound poles, and uses it to strengthen the field, instead of weakening it.

The most complete solution, however, is that given by Prof. Ryan,[4] who inserts a number of coils in slots cut in the pole-face parallel to the shaft, to receive a series winding, which thus constitutes approximately a neutralizing layer of coils with a circulation of current equal and opposite to that of the armature. Fig. 266 shows a recent design of Ryan's

[1] D. R. P. No. 34,465.

[2] *Berechnung elektrischer Gleichstrom-maschinen* (Zürich, 1892).

[3] *Electrical Review* (N.Y.), xxvii. 18, July 1895.

[4] "On a Method of Balancing Armature Reaction," *Sibley Journal of Engineering*, vii. 17, Oct. 1892; see also Ryan and M. E. Thompson, *Am. Inst. of Electrical Engineers*, 1895, where tests are given of such machines; reprinted in *Electrician*, xxxiv. 765, April 19, 1895.

with the coils arranged in slots. In such machines the magnetization does not drop with the load, nor does the neutral point shift. Further, the gap-space may be made very small, reducing the weight of the field windings. The entire absence of distortion of field at all loads is a gain; but for absolutely sparkless collection it seems better to provide a special commuting field than to depend on finding one somewhere in the fringe near the pole-tip. This Ryan proposes to accomplish as shown in Fig. 267 by bridging the space between the poles C D by an iron structure, slotted at *k l m n o p*, to receive the

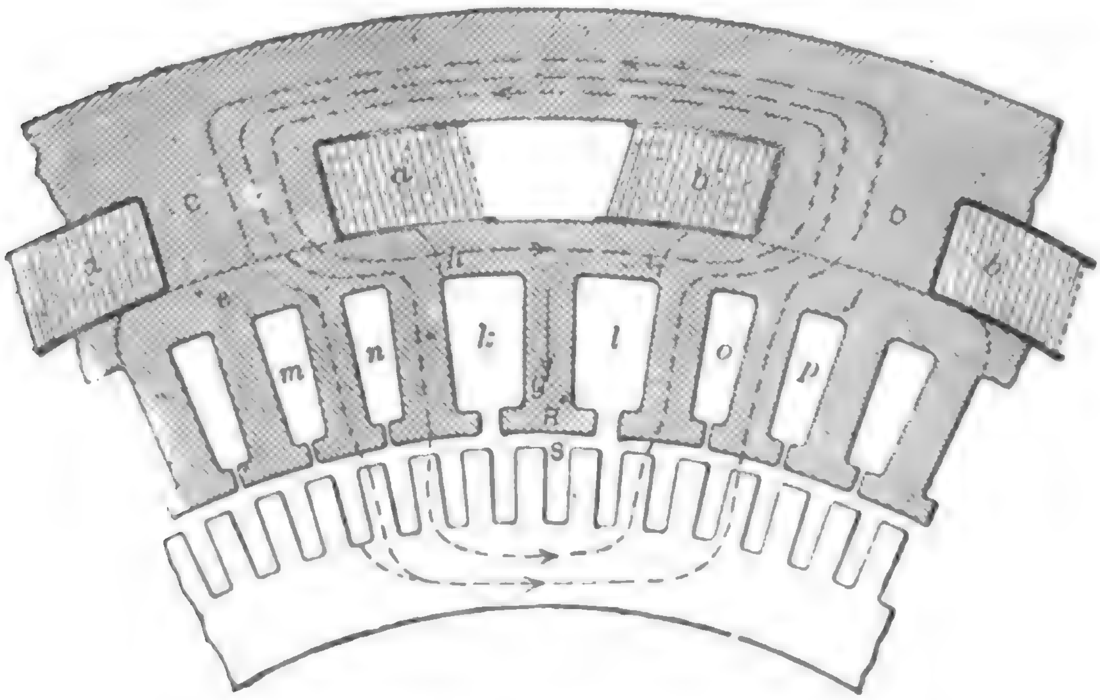


FIG. 267.—RYAN'S COMPENSATING DEVICES.

compensating conductors, and provided with a special commutating lug *g* in the centre of these windings. At no load this lug is not magnetized; but as load increases the excess of ampere-turns in these compensating windings over the cross ampere-turns of the armature tends to magnetize *g* in the direction of the arrow, giving a commutating field always proportional to the current to be commutated.

Finally MM. Hutin and Leblanc have proposed to deaden sparking by use of a device called an *ammortisseur*, consisting of a series of rods of copper carried through slots in the pole-faces all short-circuited together at their ends by being united to two rings of copper, constituting an embedded squirrel-cage.

This device (Fig. 265 *h*) is supposed to prevent oscillations in the direction of the magnetic flux which occur at commutation.

Concentration of Field.—There are other methods of preserving the requisite concentration of field at the leading edge of the pole. It is obviously desirable that the field should be magnetically *rigid*—not easily distorted. This stiffness of field can be partially secured by judicious shaping of pole-pieces. A simple notch in the pole-face, as in Fig. 265*e*, promotes concentration of the field in the tip. If the tip is itself nearly saturated, the tendency to distortion may produce

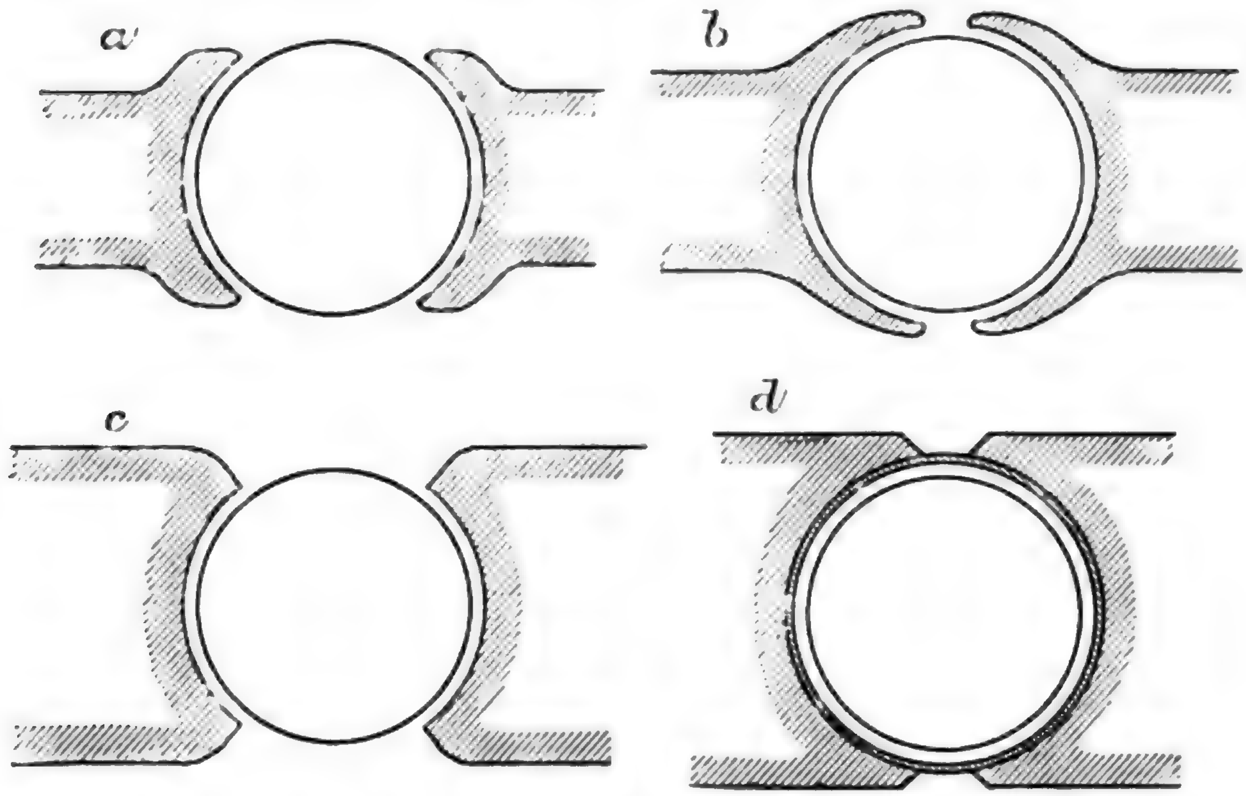


FIG. 268.—VARIOUS FORMS OF POLE-TIPS.

less effect than if it were far from saturation. But it is not on this account worth while to make the tips of cast iron instead of wrought, as they then saturate with a less flux. Tips widely separated, like Fig. 268 *a*, are not always good, even though thin. It is better that they should either be extended like Fig. 268 *b*, nearly to meet, so that they may be saturated by the leakage field, or else cut off like Fig. 268 *c*. Dobrowolsky has recommended the *bushed pole* (Fig. 268*d*), in which the armature is completely surrounded with iron.

These forms differ very greatly as to the width of *fringe* which they permit in the field. It is of advantage that the field

should present, where the conductors enter, a margin in which the flux-density varies from zero to a high value. If this margin is too narrow, the neutral point will be very well defined, and the brushes need very accurate adjustment. If it is too wide, the variations of lead at different loads may be excessive. One way of securing a suitable fringe, and at the same time maintain fair rigidity against distortion, is to bore the polar faces to a different and flatter curve, so that the polar gap is narrowest at the middle and wider at entrance and exit, as in Fig. 269. Another way, which has been found excellent by Mr. Brown, for his well-known 4-pole machines (Fig. 276), is to make the inwardly projecting poles of circular section, without any pole-shoes or extensions. The end-face of the pole when bored away presents a sufficient lip, and secures a well-gradated field of sufficient stiffness.

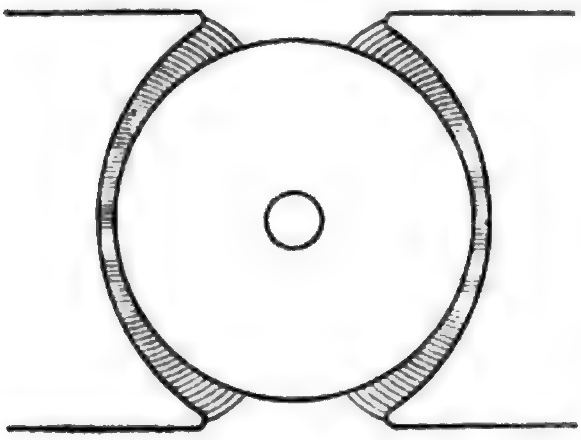


FIG. 269.—NON-CONCENTRIC POLES.

Self-compensating Armatures.—Turning to armature methods of compensation, we find several devices. Swinburne's chord winding (p. 246) diminishes the demagnetizing but not the cross-magnetizing force. It has the disadvantage that the two edges of any section are not both passing at the same instant into a commutating field; hence it is not good for handling large outputs in machines with small clearance. Its service is to give a machine which up to its spark-limit has so little demagnetizing reaction that the excitation does not require to be increased to keep up the pressure as the load increases. Edison[1] has proposed an auxiliary winding, and also other devices involving the use of two sets of brushes at different leads.

The best suggestions are those of Sayers,[2] who connects the bars of his commutator to the appropriate point on the

[1] Specification of British Patent, No. 5127 of 1883.
[2] *Inst. Elec. Eng.*, July 1893, xxii. 377; 1895, xxiv. 122.

ring or drum winding, not directly in the ordinary way by radial connectors, but through auxiliary compensating coils wound also upon the armature. One of these *commutator coils* is shown in Fig. 270, one end being attached to the junction between two main armature coils and the other end being attached to a commutator bar. At the instant before the bar comes in contact with the brush the whole armature current is being carried by a commutator coil immediately

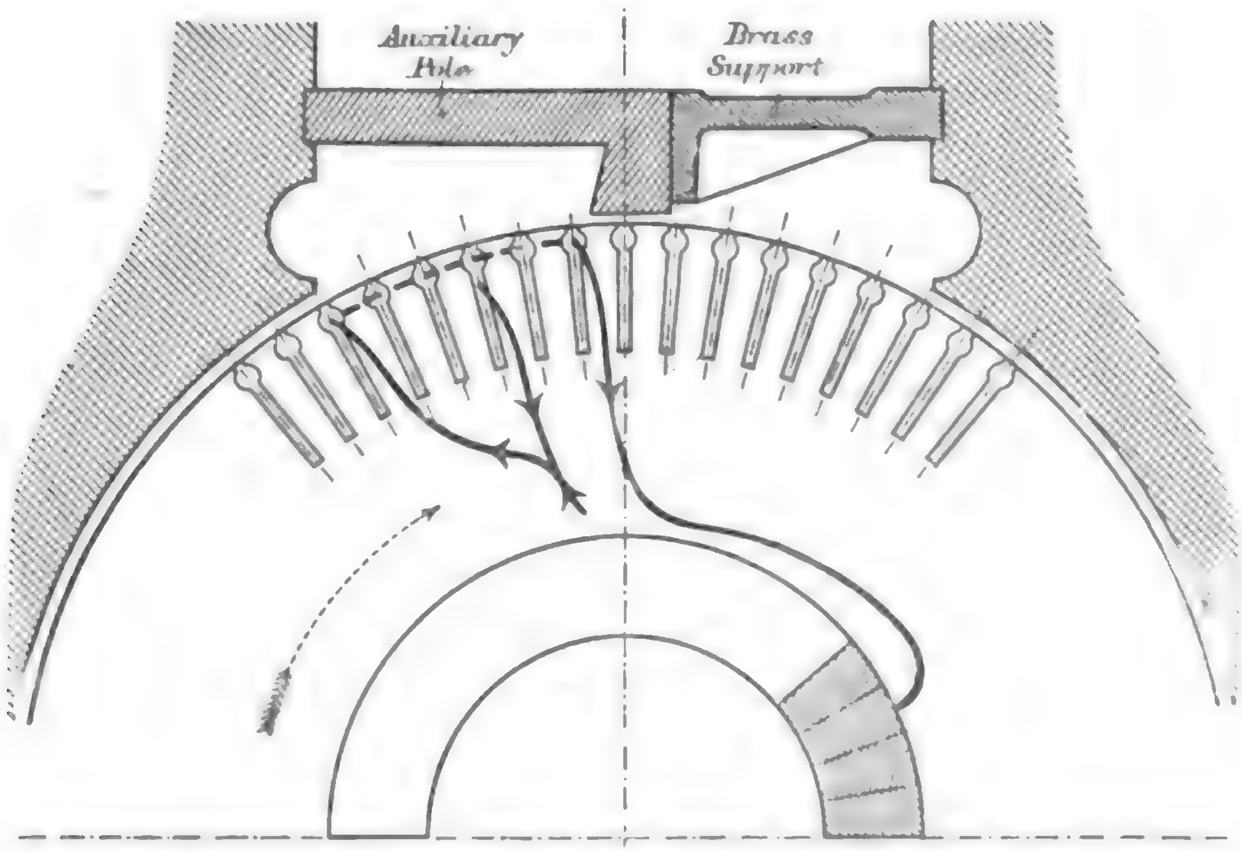


FIG. 270.—SAYERS' COMPENSATING WINDING WITH COMMUTATOR COILS.

ahead of the one shown in the figure. When the heel of the brush touches the bar, the left side of the commutator coil belonging to it is well under the pole-piece, so that it tends to take up the current; while the commutator coil preceding it has its right side just coming under the auxiliary pole, tending to stop the current in it and reverse it in the intermediate main armature winding. The commutator coil in Fig. 270 has just taken up the current. A moment later its right side will come under the auxiliary pole, which will stop the current in it and pass it on to the next commutator coil. Sometimes the auxiliary pole is wound as shown in Fig. 263. The main advantage of Sayers' winding is that instead of

putting the brushes forward, he is able to give them a *backward lead*, so that the armature current exercises a helpful magnetizing action, and obviates the need of any compound winding on the field-magnets. (See also p. 438 and Plate XII.)

Design of Multipolar Dynamos.

Bipolar machines are common for small dynamos, but for large outputs multipolar are preferred.

The advantage of using Q (the circumflux) rather than the ampere-turns, in the investigation on pp. 384 and 385, was that the spark limit of load depends not on the total ampere-turns or action of the whole armature as an electro-magnet, but on the circulation of current per pole. Hence the results already obtained are available for multipolar machines, as was pointed out by Esson, to whom is due the credit of this conception.

The second formula on p. 384 may now be re-written—

$$Q = \frac{577\ \mathsf{B}\ l_2}{\psi};$$

where B is the strength of field in the gap-space.

If we assume the limiting values of Q, and the usual value of B, as already determined, then if ψ, the angle of polar span, be taken at 130°, it follows that the radial depth l_2 of the gap-space must not be less than $\frac{1}{28}d$. for rings, nor less than $\frac{1}{18}d$. for drums. Then, if in order to make a large output machine, whilst keeping to two poles, we increase d, we must either increase l_2 or B, or else diminish ψ, or perform some combination of these processes, which in any case involves a greater expenditure of power in maintaining the field in the gap-space. Herein lies the advantage of multipolar construction for large outputs. Consider such a form as Fig. 271 with 4 poles. To prevent undue leakage from pole to pole the distance between pole horns is wider relatively to the polar span than in a 2-pole machine; and, for an equally high value of B in the gap-spaces, the section of the ring is reduced, its diameter enlarged, and with its diameter its cooling surface.

For drum-wound machines there is, in addition to such gains, the additional advantages that end-connections are much simpler, and ventilation easier, than for 2-pole machines. But does it pay the constructor to make the change? There is a little more labour in tooling castings; but will he save copper? A case will show that, beyond a certain limit of size, there is a saving. Consider a 2-pole drum; $d=50$; $L=90$; $\mathsf{B} = 5000$ in the gap; $\psi = 130°$. Then it will not be sparkless unless the gap-space l_2 is at least 3·2 cm., or about

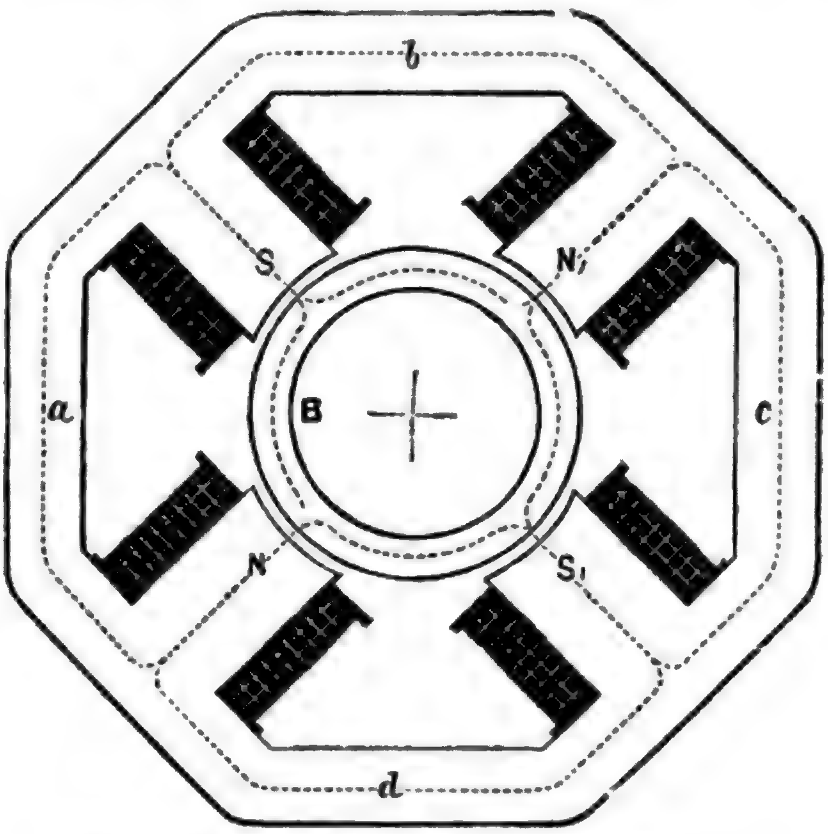


FIG. 271.—FOUR-POLE MAGNET (BROWN).

0·9 cm. more than is needed for windings and clearance. If, to make this work sparklessly, we diminish the gap and increase B to 7000 or diminish ψ to 100°, we still gain nothing in magnetizing power. Now substitute a 4-pole drum: $d = 84$; $L = 45$; $\mathsf{B} = 5000$. With this increased diameter, the gap-space may be reduced to a minimum, the magnetizing power may be reduced by at least 30 per cent., and the total weight of iron by nearly 40 per cent., which will more than pay for the extra labour of tooling. Esson states that the cost of a 4-pole dynamo, of output W at speed n, may be put as being equal to that of two dynamos, each of out-

put ½ W at speed $2n$, and so forth. The cost of field-magnet castings is reduced, and their weight lessened, when, as in the large machines of Siemens and Halske (Plate VIII.), the ring is of such large dimensions that the field-magnet can be placed internally.

For machines exceeding 100 kilowatts multipolar forms are, then, generally preferable to bipolar; firstly, because they give their maximum sparkless output with minimum clearance, and therefore with minimum weight of copper on magnet; secondly, because they keep cooler, so that for a given volume of core and winding there is actually a greater output. Multipolar machines have one further advantage over bipolar machines, in that their length may be shortened relatively to the diameter without loss in economy, and with great mechanical gain. In the case of drum windings this is very marked.

Best Thickness of Gap-space.

Professors Ayrton and Perry have investigated[1] the rule for the best thickness of the conductors on armatures. By finding an expression for the total heat-waste in terms which included the heat wasted in the excitation needed for the different parts of the reluctance, and considering what relations between these would make this waste a minimum, they came to the following conclusion:—The permissible continuous output of the machine is a maximum when the thickness of the winding on the armature is such that *the magnetic reluctance of the space occupied by the winding on the armature is equal to the reluctance of the rest of the magnetic circuit.*

Assuming that practically the whole of the gap-space between armature-core and pole-piece is filled with armature winding, the above rule amounts to saying that, given the construction of armature, the dynamo ought to be worked at such a degree of excitation that its total magnetic reluctance is run up to be twice as great as that of the gap-space alone. This is indeed no other than the diacritical stage of magnetization, the permeability in gross of the magnetic circuit—iron and air together—being at this point reduced to half its initial value.

[1] See their paper, *Phil. Mag.* for June 1888; or page 444 of the fourth edition (1892) of this work.

CHAPTER XVII.

EXAMPLES OF CONTINUOUS-CURRENT DYNAMOS.

CONTINUOUS-CURRENT dynamos are made in different patterns for different kinds of service, and differ not only in size, but in the voltage at which they are designed to operate. The chief varieties are enumerated below:—

For incandescent lighting and general distribution at constant pressure. Usually at 100 to 110 volts. Occasionally for isolated plants at 50 or 60 volts. Occasionally at 120 or 125 volts.

Ditto for three-wire distribution, 200 to 250 volts.

Ditto for five-wire distribution, 400 to 500 volts.

All the above are usually shunt-wound for station use, or compound wound for isolated plants.

For *tramway generators* 400 to 500 volts, usually shunt-wound, or compound-wound, or over-compounded.

For *arc-lighting in series*, usually series-wound, to operate at 10 amperes, voltage varying up to 2000 or 3000 volts.

For *accumulator-charging*, shunt-wound, with magnets not too highly magnetized.

For *electroplating, electrotyping, and electrochemical processes*, usually shunt-wound, at low voltages, but to carry very large currents.

For *long-distance transmission of power*, usually series-wound at 1000 to 2000 volts, or more, though for this purpose alternate-current machines are preferable.

In the present chapter no attempt is made to describe or enumerate all the modern machines in the market. A few leading varieties only are mentioned, many excellent machines by first-rate firms being necessarily omitted for want of space. In former editions of this book many forms have been described that are now omitted. In the French edition of this

work the translator, M. Boistel, has added a valuable supplement describing the current types made in France.

Gramme Dynamos.—Innumerable forms have been given to the Gramme machine at different dates since its appearance in 1871, varying from small laboratory machines with permanent steel magnets, such as are shown in Fig. 7, p. 14, to large machines absorbing several hundred horse-power. Those who desire more detailed information concerning the various patterns of Gramme dynamo should consult the earlier editions of this work, in which a number of forms[1] were described.

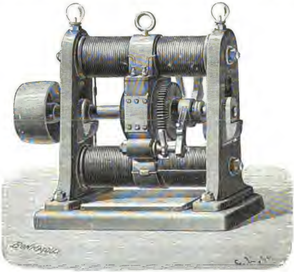


FIG. 272.—GRAMME DYNAMO, "A" PATTERN.

---

[1] Amongst these are the improved forms designed by M. Marcel Deprez, those designed by Mr. Hochhausen, and those made by the Fuller Company of New York; Mr. Wood, of New York, has also perfected the design in many details. Other modifications have been made by M. Raffard, by MM. Sautter Lemonnier and Co., and by other French engineers: of these, some account is given in *Industries*, Nov. 5th, 1886. For an account of Gramme's historical exhibit in the Paris Exposition of 1889, see *Industries*, vii. 285, 1889. Consult also the work entitled *Éclairage Électrique*, by H. Fontaine, upon the electric lightingof the Paris Exposition, published in 1890. A new slow-speed machine of multipolar type, designed by Gramme in 1892, with flat-ring on the Schuckert plan, is described at p. 838 of the French edition of this book translated by M. Boistel.

They should also refer to the treatise of the late Alfred Niaudet, entitled *Machines électriques à courants continus, systèmes Gramme et congénères* (1881). Fig. 272 shows the ordinary "A" Gramme, the first pattern which came into commercial use, and which, with little alteration save general strengthening of the design, remains in use to-day. Its characteristic features are the ring-armature, made of an iron wire core entirely overwound with coils (described p. 41), and the double-circuit field-magnet having consequent poles above and below the armature.

Crompton's Dynamos.—Mr. R. E. Crompton, who pioneered many of the improvements in recent years, has brought the smooth-core armature machine to a high pitch of perfection.

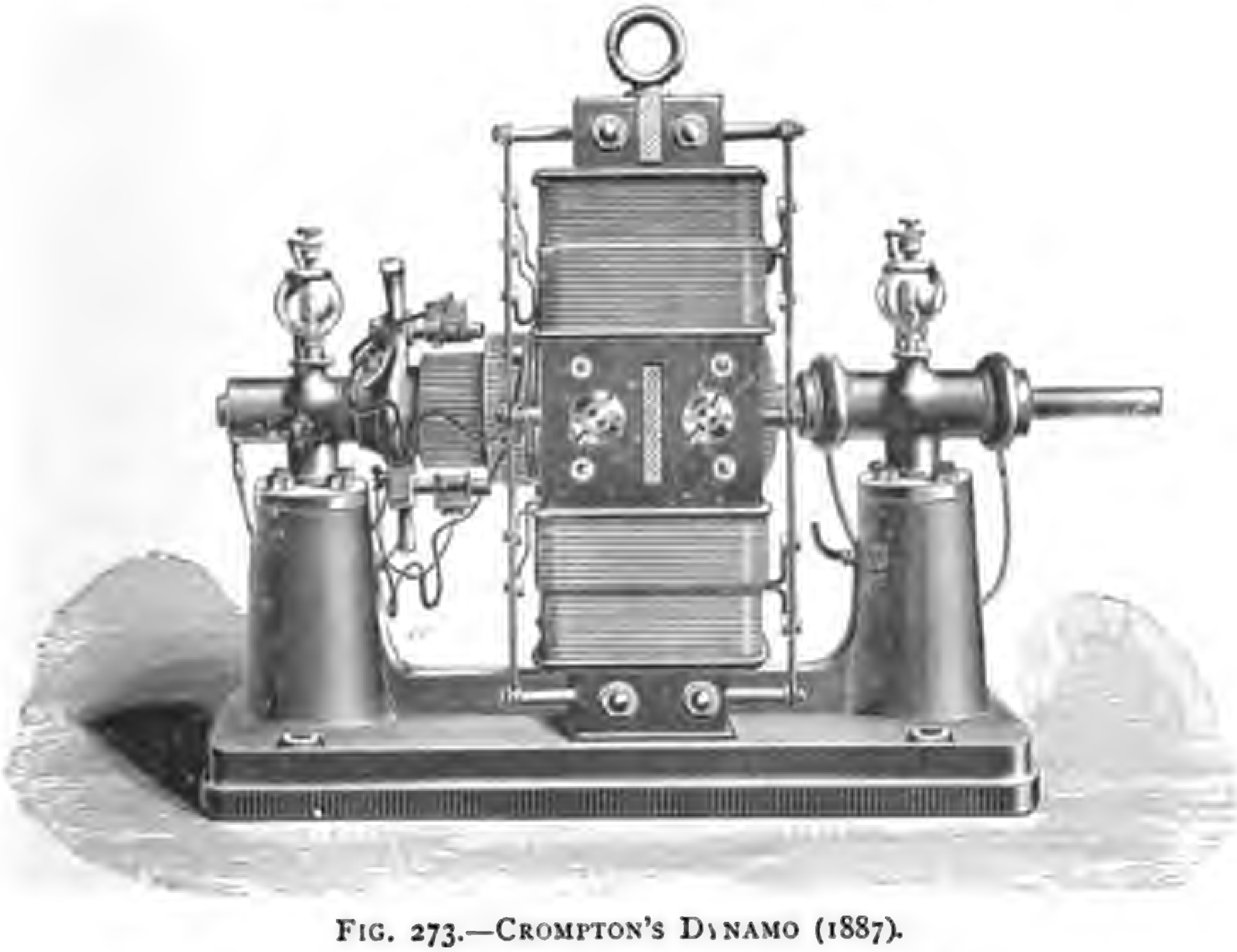


FIG. 273.—CROMPTON'S DYNAMO (1887).

A general view of the Crompton dynamo is given in Fig. 273, which shows vertical field-magnets with a double magnetic circuit.

In some of the most recent machines a single magnetic

circuit only is employed. In the larger 4-pole machines for central stations the magnets have the form of Fig. 101, No. 27, whilst drum-armatures are used, of the construction shown in Fig. 236, p. 308. Another improvement useful in machines for furnishing large currents consists in dividing each conductor on the external periphery of the armature into two or more strips, which are crossed under one another at the middle and united together at their ends. Instead of such *imbricated strips*, rectangular bars of *compressed stranded wires* are now used in all large output machines. This construction greatly diminishes the eddy-currents which are set up in the conductors on the surface of smooth cores if they consist of single rods or solid bars.

A complete account of Mr. Crompton's successive stages of improvements[1] would occupy a volume in itself. Besides the improvements made in conjunction with Mr. Kapp on general design, pp. 291 and 301, and more favourable use of iron in the armature, a number were made in conjunction with Mr. Swinburne on various modes of winding, p. 307, and on machines with conductors embedded in the core-disks. Then Mr. Crompton found that it was needless to insulate core-disks from spindle if they were separated from one another throughout their surfaces up to the periphery. Next came the question of driving-teeth, and the thick driving-disks mentioned on p. 296 were abandoned in favour of teeth of delta-metal or aluminium bronze, fitted into the substance of the compressed core. Then came the production of imbricated and compressed stranded conductors to obviate eddy-currents. Lastly, the adoption of multipolar series windings for drum-armatures. With large 4-pole machines for central-station lighting Messrs. R. E. Crompton & Co. have had great success. The construction of some of their large-output armatures is indicated in Figs. 235 and 236, on p. 308.

Kapp's Dynamos.—Mr. Gisbert Kapp has designed various forms of direct-current dynamos, some having cylindrical

[1] See remarks by Mr. Crompton in *Proc. Inst. Civil Engineers*, lxxxiii. 125, 1885; *Journal Soc. Teleg. Engineers*, xv. 546, 1886; and *Journal Inst. Elec. Engineers*, xix. 239, 1890, and xx. 308, 1891.

ring-armatures, the more recent ones drum-wound armatures. The best construction of 2-pole machine is that depicted in Fig. 259, p. 359, being of the "over" type with the armature and shaft at the summit of the field-magnet. These machines were constructed first by Messrs. W. H. Allen & Co., later by Messrs. Johnson and Phillips. In Plates I., II., and III. are given drawings of a 21-unit machine by the latter firm, giving 200 amperes at 105 volts at 780 revolutions per minute. The following are the data of this machine (and see p. 357):—

Armature. Core 16" long by $2\frac{3}{8}$" deep, mounted on cast-iron spider. Area of iron in core, allowing for insulation between core-disks, 62·5 sq. in. External diameter $11\frac{1}{32}$". Conductor 120 copper bars, each made of two parallel bars, 0·208" × 0·110" in section, united in parallel, affording 0·046 sq. in. sectional area. Connectors 120 copper semicircles with lugs; depth $1\frac{5}{8}$"; thickness, 0·050". Resistance (hot) 0·025 ohm. Commutator 60 parts.

Field-magnets. Diameter of bore, $11\frac{15}{16}$". Shunt winding 11 layers, of 139 turns each, of 0·065" diameter round copper wire, covered to a diameter of 0·080", on each limb, and the two limbs connected in series. Total shunt turns 3058. Series winding 23 turns on each limb of copper tape, 0·480" wide by 0·130" thick, and the two limbs joined in parallel. Resistance of shunt coils (hot) 30·8 ohms; of series winding 0·0079 ohm.

One peculiarity in this dynamo is the mode of driving the conductors of the armature. As shown in the section in Plate II., there are introduced at intervals between the core-disks, some thicker disks having ventilating apertures and projecting horns of steel. Around these steel horns are placed pieces of hard white fibre, as driving-horns; and as these project in alternate positions, the copper conductors cannot be laid straight, but are given a sinuous form. Plate II. also shows how the core-disks are clamped together by face-plates having ventilating perforations through them, the whole core being held up against a collar on the shaft by a screw-nut. The figures in Plates I., II. and III. also show the details of the brush-holder and rocker, the construction of the field-magnet, the arrangements of the bearings, and the pattern of lubricator employed.

Mr. Kapp has also designed some multipolar drum dynamos for central-station lighting. In the previous edition of this book there was described a 6-pole machine with the armature windings grouped in series so as to need but two sets of brushes. The windings are of a cable of stranded insulated wire.

Siemens' Dynamos.—These originated with Messrs. Siemens and Halske, of Berlin, who have manufactured many different

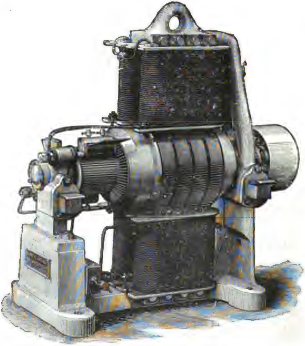


FIG. 274.—SIEMENS' DYNAMO (Vertical Pattern).

forms. In recent years there has been some divergence between the types followed in Berlin and those produced by the London firm of Siemens Bros. Until about 1890 the characteristic feature of all forms was the drum-armature; but the largest machines are now made with rings. In some of the earlier patterns of Siemens' machines the cores of the

drum were of wood, over-spun with iron wire circumferentially before receiving the longitudinal windings. In another of their machines there was a stationary iron core, outside which the hollow drum revolved; in other machines, again, there was no iron in the armature beyond the driving-spindle. In all the modern drums iron core-disks are now used. The old horizontal pattern of Siemens' dynamo is depicted in Fig. 8, p. 15. This was followed about 1880 by the vertical form shown in Fig. 274. The field-magnets here consist of forged arched bars of wrought iron, with double magnetic circuit, having consequent poles right and left of the armature. About 1882 various ways of compound-winding were tried,[1] in some of which the series and shunt-coils were wound on the same cores, and in others on different limbs, the usual practice being to wind the series-coils outside the shunt windings. Some large machines of this vertical pattern, including three 112-kilowatt compound-wound dynamos, were used at the Inventions Exhibition of 1885. Each of these was capable of yielding 450 amperes at 250 volts at 300 revolutions per minute.

In 1886 Messrs. Siemens and Halske, after trying some intermediate forms (depicted in former editions of this book), adopted for outputs of from 1 to 80 kilowatts the over-type with field-magnet consisting of a single very massive casting. The commutators were of iron bars attached by screws at one end only, so as to be replaceable, and insulated by air-gaps. The largest size has a peripheral speed of 2730 feet per second.

The London firm has constructed much larger drum machines for central-station lighting, mainly of the under-type. Fig. 275 represents one of these machines, compound-wound, with the series winding on one limb only. At the Naval Exhibition of 1891 were shown three fine dynamos of 180 kilowatts each, at the slow speed of 350 revolutions per minute. The armature is 24 inches in diameter, 36 inches long, and weighs 2·4 tons; and the entire dynamo weighs 13·6 tons. The armature conductors are stranded bars; the

[1] See series of papers in the *Elektrotechnische Zeitschrift*, March–June, 1885, by D. O. Frölich.

commutator of hard-drawn copper, insulated with mica, with 144 segments, 9 inches long, with three pairs of brushes to collect the 1500 amperes. The rocker is provided with worm-wheel to adjust the proper lead. There are two independent circuits of 72 turns each, which are put in parallel with one another by the brushes, which are made broad enough to overlap three consecutive bars of the commutator.

Towards the end of 1886 a form of multipolar ring machine, with ring external to the field-magnets, was brought

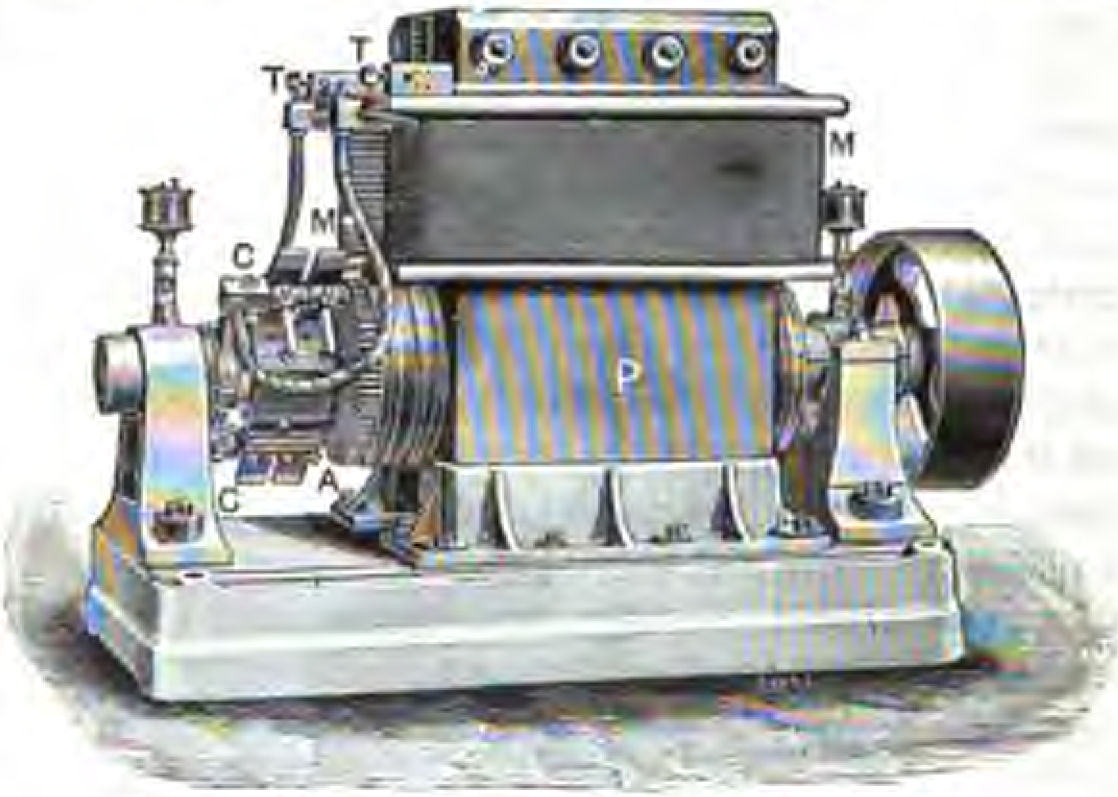


FIG. 275.—SIEMENS' DYNAMO (London type of 1890).

out almost simultaneously by Messrs. Ganz of Buda-Pesth, Messrs. Fein of Stuttgart, and by Messrs. Siemens and Halske of Berlin.[1] It will be sufficient to describe the machines of the latter firm.

The field-magnet is stationary and internal to the ring. In the small machines this consists of a substantial cross-shaped mass of cast iron, through the centre of which passes the driving-shaft. The four poles, after receiving the exciting coils, are furnished with polar expansions, which approach

[1] For further information about the various machines of this type see *Elektrotechnische Zeitschrift* for April and May, 1887; *La Lumière Électrique*, xxiv. 182, 1887; *Centralblatt für Elektrotechnik*, ix. 186, 410, and 581, 1887, and the Official Report of the Frankfort Exhibition of 1891.

close to the inside of the ring. The ring core is made up of thin iron washers bolted together, and is overhung, being supported on one side by a brass spider keyed to the shaft. A machine of this type, weighing 2660 lbs., with an output of 25 kilowatts at 480 revolutions per minute, had a ring 20 cm. broad and of 64 cm. internal diameter. The advantages of this type are the ease of repair, the immense cooling surface of the armature, and the non-necessity of applying binding-wires. In the larger machines the brushes are applied against the exterior of the ring itself, with the result that the most noticeable feature of the machine is the enormous commutator and the huge star-shaped brush-holder which supports the various sets of brushes (see Plate VIII.).

In the central stations of Berlin and other German cities these large dynamos are combined with huge engines of the marine type, the whole having a very imposing appearance. In Plate VIII. are shown some of these machines, the largest hitherto made, in the station at Schiffbauerdamm, Berlin. The dynamos are mounted in pairs on the ends of the main shaft of an enormous compound condensing-engine of marine type, by Kerchove and Co., of Ghent, having 5 feet 5 inches stroke, the diameters of the cylinders being respectively 2 feet 6 inches and 4 feet 5 inches, giving 1180 indicated H.P., or 1000 actual H.P., at 75 revolutions per minute. Each dynamo is capable of giving 2000 amperes at 140 volts, at only 60 revolutions per minute. The field-magnet has 10 salient poles, with rectangular cores fixed to an annular yoke-ring, which is carried in a U-shaped support on the bearing. The exciting coils are all joined together in series, and connected in shunt to the armature. The armature is built of core-rings mounted on insulated arms, which project from a bronze star-wheel, thus overhanging the field-magnet. Fig. 229, p. 302, shows the detail of construction. The winding, as that figure shows, consists exteriorly of straight copper bars, united by other pieces of bent form which pass through the inside of the ring from the end of one straight bar to the beginning of the next, thus constituting a spiral and endless winding. The collecting brushes trail against the exterior of the periphery of the

armature, which thus serves as commutator, and is 9 feet in diameter. The brush-holders are mounted on a stellate rocker, by which they can all be simultaneously shifted forward or back. The brushes can also be all raised simultaneously out of contact by a lever *f*, united by connecting rods to another star-piece. Plate VIII. shows separately the star-shaped rocker. At the Spandauerstrasse station are four such engines of 1000 nominal H.P., each driving two dynamos, supplying in total 40,000 to 50,000 lamps. At the Markgrafenstrasse station are four single steam dynamos of 400 H.P. each. At the Mauerstrasse station are three double steam dynamos of 1000 H.P., and two single of 400 H.P. each. At the Schiffbauerdamm station are six double steam dynamos of 1000 H.P. each.

At the Frankfort Exhibition of 1891 a similar 300 kilowatt dynamo was shown[1] direct-driven from a triple condensing engine by Kuhn of Stuttgart, giving 2200 amperes at 150 volts at 65 revolutions per minute. The magnet of this dynamo had 10 poles, being 272 cm. in diameter. The external diameter of the ring was 310 cm., wound with 810 convolutions, each bar being about 1 cm. wide, with paper insulation. There were 10 sets of brushes, three in each set, each brush being 4·5 cm. wide, of rectangular copper wire. The star-piece carrying the overhung armature was of cast iron, with 30 arms, supporting the core-disks by means of 30 insulated steel bolts. To collect the currents the five positive brush-sets are united together, and the five negatives are also connected together; the currents being conveyed to the mains by flexible cables. At a speed of 100 revolutions per minute this machine reaches an output of 600 kilowatts.

Oerlikon Co.'s Dynamos.—For many years past the Oerlikon Machine Works near Zürich has produced excellent machines. Till 1892 the chief designer was Mr. C. E. L. Brown. Since that date Mr. Kolben has been mainly responsible. Of their many types of machine but a few can be described.

PLATE IV. *Glow-lamp Dynamo*, 28 *kilowatts.*—Output

[1] See description by Esson in *Electrical Review*, xxix. 34?, 1891.

400 amperes at 70 volts; 38 H.P. at 400 revolutions per minute. This machine resembles the "Manchester" type, but is even more massive, and is now made with drum instead of ring winding. The core-disks are keyed to a long sleeve, and they are pierced to receive the copper conductors; the perforations being 12 mm. in diameter, sunk 1 mm. below the

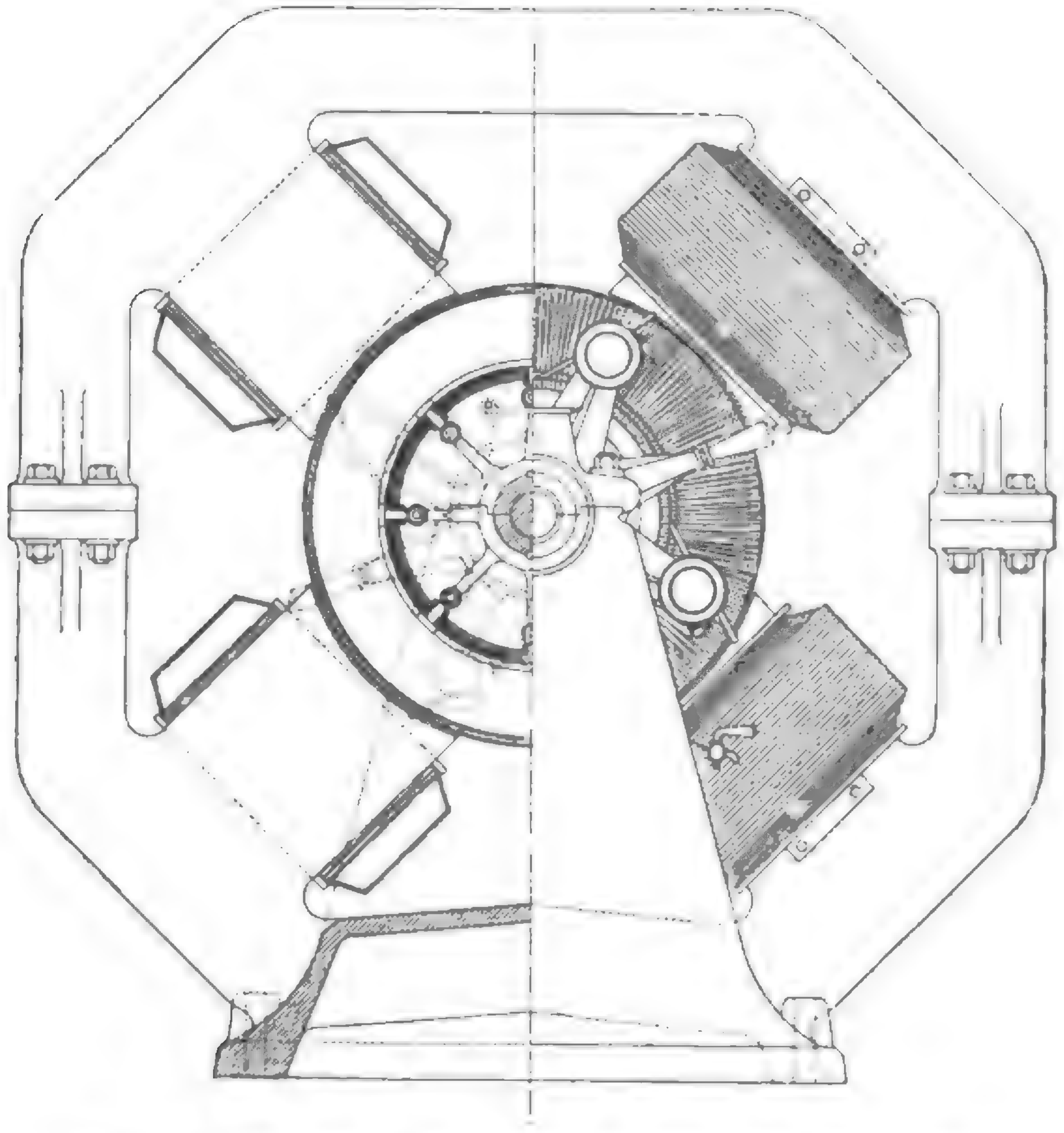


FIG. 276.—BROWN'S 4-POLE DYNAMO (OERLIKON CO., 1889), END VIEW. (Scale 1 : 24.)

periphery. The thickness of the gap-space from iron to iron is thus reduced to 2·5 mm. Core-disks, external diameter 51·4 cm., internal diameter 22 cm., thickness 0·6 mm.; number 570, insulated with paper. Total sectional area of iron in armature 480 sq. cm. Number of conductors around periphery, 80; commutator bars, 40; resistance of armature,

brush to brush, 0·00525 ohm. Field-magnets, shunt wound with 2800 windings of wire, 3·2 mm. diameter; resistance 6 ohms, with about 1 ohm extra in series for regulation at above speed and output. Conductors passing through holes in armature are round copper 9·2 mm. in diameter. The end-connectors are of strip copper in two-legged pieces bent into evolute spiral shape, as in Fig. 232, p. 305.

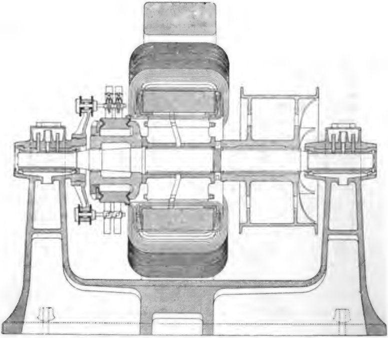


FIG. 277.—BROWN'S 4-POLE DYNAMO. LONGITUDINAL SECTION.

Figs. 276, 277, and 278. *Four-pole Ring Dynamo for Transmission of Power*, 170 *kilowatts*.—Output 270 amperes at 625 volts; 240 H.P. at 500 revolutions per minute. These machines, of which two were shown in the Paris Exposition of 1889, stand nearly 8 feet high. They are ring-wound, with the windings external to the core-disks, as the construction with conductors embedded in holes was not thought suitable

then for machines exceeding 100 volts. The cast-iron magnets are arranged radially, and are united by a very massive yoke ring, the lower half of which is cast in one piece with the frame and the supports for the bearings. The armature is 96 cm. in diameter, and 50 cm. deep. Core-disks,

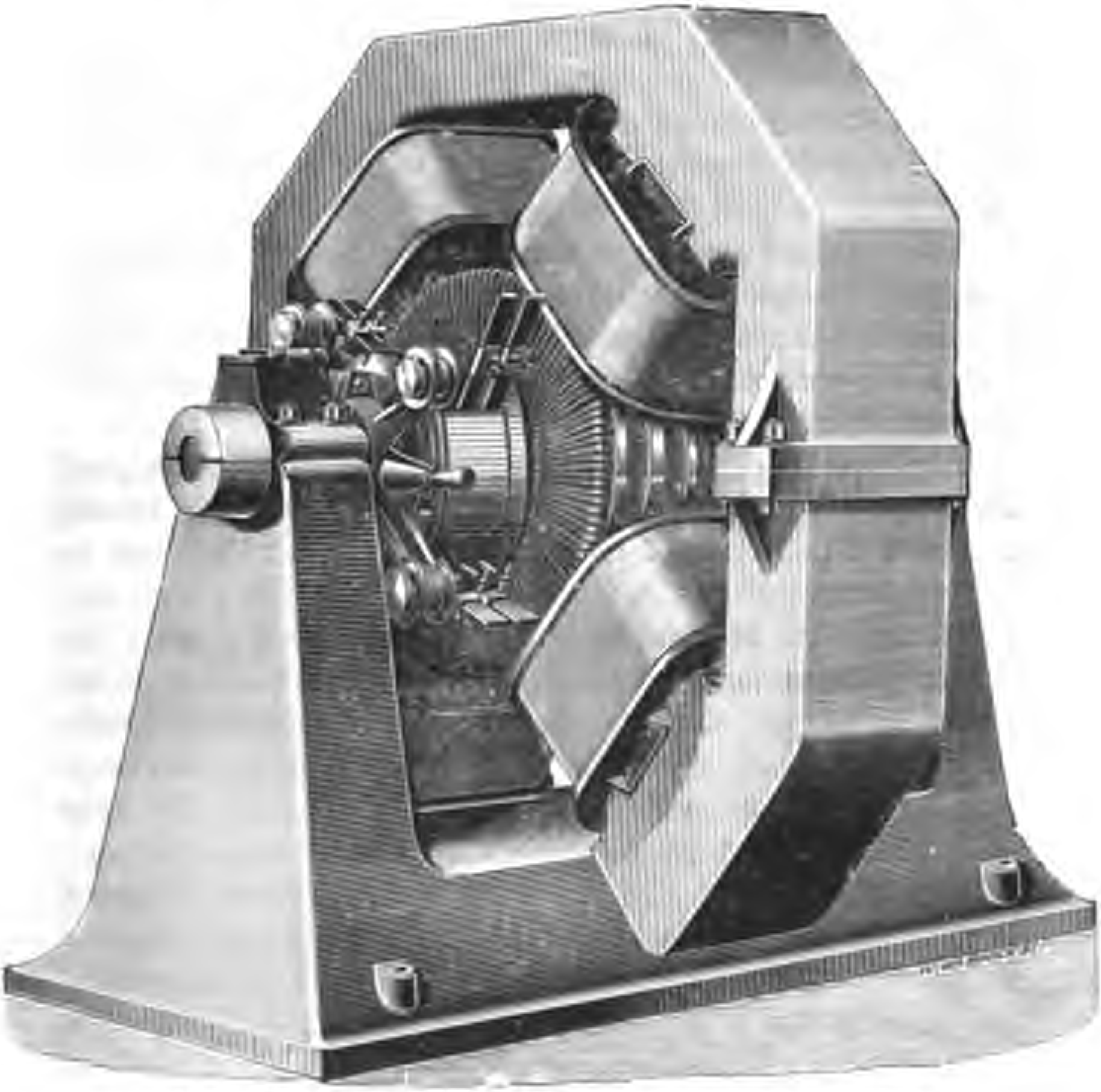


FIG. 278.—BROWN'S 4-POLE DYNAMO (OERLIKON CO., 1889).

internal diameter 66 cm., external diameter 96 cm., thickness 0·6 mm., insulated with paper; net sectional area of iron in ring, 660 sq. cm.; gap-space, iron to iron, 16 mm.; winding (generator) 400 turns of cable containing 19 strands of 1·3 mm. wire, wound in one layer externally and two layers internally;

resistance, brush to brush, 0·025 ohm.; cross-connections, none; commutator, 200 parts. Field-magnet coils in series with armature, and are each wound with 60 turns of 1 mm. copper sheet 30 cm. in width. Weights are as follows:—Frame and magnet cores 11,600 kilos, armature iron 1430, armature copper 132, armature complete 2420, magnet copper 1370. Total weight of complete machine, 15,700 kilos, or nearly 16 tons. At 500 revolutions per minute, it can be run at 250 H.P. continuously night and day. If run in day only the current may be increased so as to work at 300 H.P. Commercial efficiency at full load 93–94 per cent.

The machine used as motor, with the above generator, is nearly identical, the only difference being that there is slightly less iron in the armature, and there are only 364 windings with a 184-part commutator. Modified in this way the speed is constant, though the loss in the line varies with the load.

Fig. 279. *Eight-pole Ring Dynamo for Electrometallurgical Purposes.*—For the use of the aluminium industry Mr. Brown designed 6-pole and 8-pole dynamos. That depicted in Fig. 279 was a 300 H.P. machine working in the aluminium establishment at Neuhausen. This was the first dynamo of the vertical pattern designed to run upon a vertical turbine. With an average output of 3000 amperes the machine runs sparklessly. The mode of cross-connecting each part of the ring-winding to the two points of the commutator 45° distant is accomplished by bent two-legged strips of copper, as shown.

Fig. 280 depicts a 24-pole vertical shaft dynamo, designed in 1891 for the aluminium industry. The moving armature weighs 12 tons, and revolves at 150 turns per minute; total height, 12½ feet; total weight, 34½ tons. Its output is 7600 amperes at 55 volts; being about 600 H.P. To collect this current there are 24 ranks of brushes, 5 brushes in each rank, equi-spaced around a commutator 1·7 metres in diameter. The commutator is below the armature, which is drum-wound, having stranded conductors laid in perforations through the core-disks. The field-magnet is constituted of a crown of 24 inwardly-pointing poles of cast iron; it is supported upon a ring of masonry exterior to the machine.

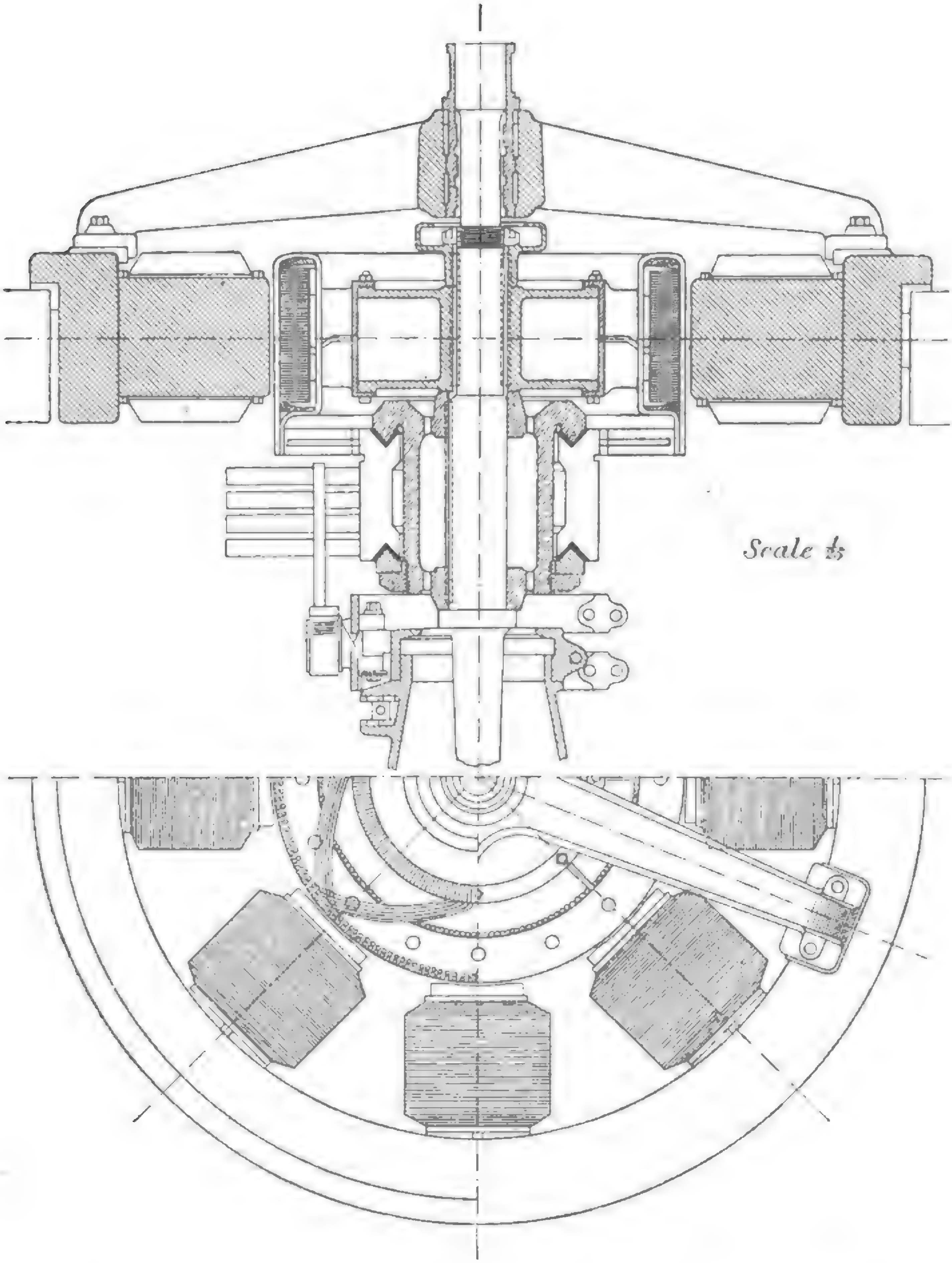


FIG. 279.—VERTICAL-SHAFT 8-POLE DYNAMO FOR USE WITH TURBINE (OERLIKON CO.).

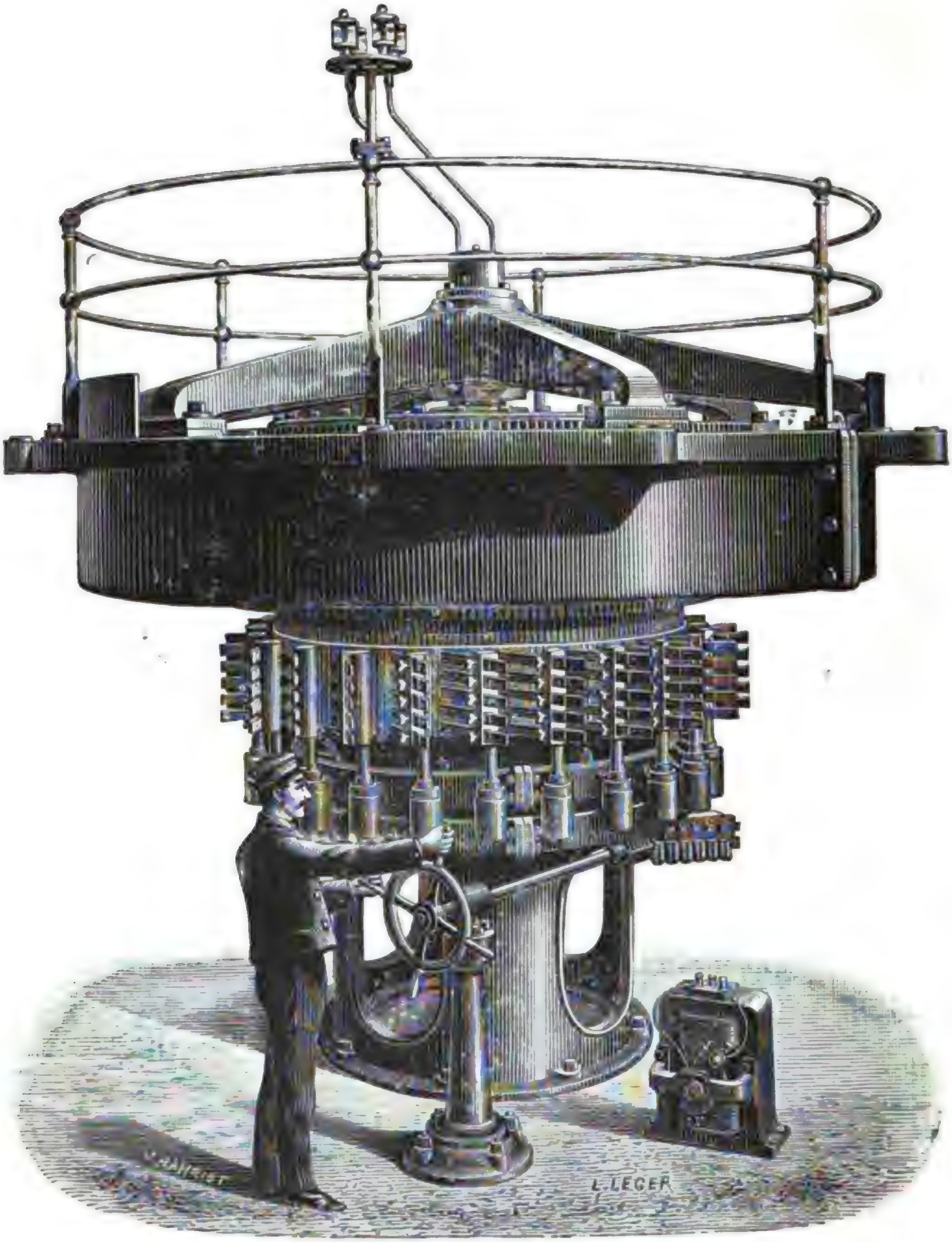


FIG. 280.—OERLIKON CO.'S DYNAMO FOR ELECTROMETALLURGY.

The Oerlikon Co. has built numerous other vertical shaft machines for turbine work, amongst them being the alternators described in Chapter XXIII.

Fig. 281 depicts a 60 kilowatt 4-pole machine, which may

be regarded as a development from the earlier form of Fig. 278. The armature is, however, drum-wound. It was separately shown in Fig. 237.

Brown's Dynamos.—Since 1892, when the firm of Brown, Boveri & Co. began operations, Mr. Brown has designed many types of machines, notably those of the vertical-shaft

FIG. 281.—OERLIKON CO.'S 4-POLE 60 KILOWATT DYNAMO (1895 type).

type for turbine use. Plate VI. gives a view of a recent 4-pole continuous-current machine used as exciter for the large "umbrella" alternators in the turbine house of the town of Aarau. The armature has the cylindrical winding described on p. 310.

Fig. 282 illustrates a special 6-pole dynamo designed by Brown for use on the Heilmann locomotive: a service for which lightness of weight relatively to output is essential. As it must run at a high speed a ring-winding is preferred. The

actual weight is less than 26 lbs. per horse-power. It weighs, without the hinder bearing, 7200 kilogrammes, the armature being 2400 kilos. Its normal output is 600 H.P., its maximum 750. At 400 revolutions per minute it gives out 920 amperes at 455 volts. It is separately excited, and direct-driven.

Messrs. Brown, Boveri & Co. continue to use the bipolar type of Plate IV., but the new designs have more massive

FIG. 282.—BROWN'S 6-POLE DYNAMO FOR THE HEILMANN LOCOMOTIVE.

yokes with a deep V-shaped depression at the middle. For transmission of power they have recently built some of these machines with the magnets in the main circuit, carrying 40 amperes at 2500 volts. For all ordinary lighting and distribution of power their type for continuous currents remains, however, the 4-pole machine much on the lines of Fig. 278. The armature, however, is the cylindrical drum described above (Fig. 240, p. 311); and the magnet cores are of circular section without any polar expansions. The field-magnet then

consists simply of two castings bolted together, with the pole-faces bored out.

Brush Co.'s Dynamos.—The Brush Electrical Engineering Co. manufactures several different types of continuous-current dynamos. For small sizes the type preferred is of the bipolar over-type, having magnets and bed-plate cast in one, and a simple drum armature. For outputs from 1 to 7 kilowatts a machine of "Manchester" type with ring-winding is used. For outputs up to 36 kilowatts and for motor work, the type preferred is a 4-pole machine with armature of the flat-ring type, produced under the patents of Mordey, Wynne, and Sellon, to which the not very apt name of the "Victoria" dynamo has been given. The development of the Victoria machine from the original Schuckert machine commenced with the discovery by Mr. Mordey, by the aid of his method of examining the distribution of potentials round collectors, that by reducing the size of the pole-pieces to make space for a 4-pole field, the electrical output was doubled, without increase of speed, when using the same ring as employed by Schuckert with a 2-pole field. The pole-pieces in the earlier Schuckert machines consisted of hollow iron shoes or cases which occupied a large angular breadth along the circumference of the ring. The Mordey-Victoria machine has a narrower form of pole-piece, not covering more than 35° of angular breadth of the circumference of the armature. Fig. 283 represents the 4-pole Victoria dynamo as now constructed. The pole-pieces are of cast iron shrunk upon the cylindrical cores of soft wrought iron which receive the coils. The armature of the Victoria dynamo has several times been modified, and its core is now made of almost square section. It is built up of charcoal iron tape, coiled upon a strong foundation ring, contact between successive layers being prevented by coiling paper between. Special pains have been taken throughout to ensure that there are no electric circuits made in the bolting together of these cores, each layer being insulated from the adjacent layers. Eddy currents in the core are thus almost entirely obviated. The foundation ring and some of the inner convolutions of tape are slotted out to

receive the gun-metal arms, of which there are two sets clamped together, one on either side. Fig. 283 shows this construction and the method of securing the ring to the shaft

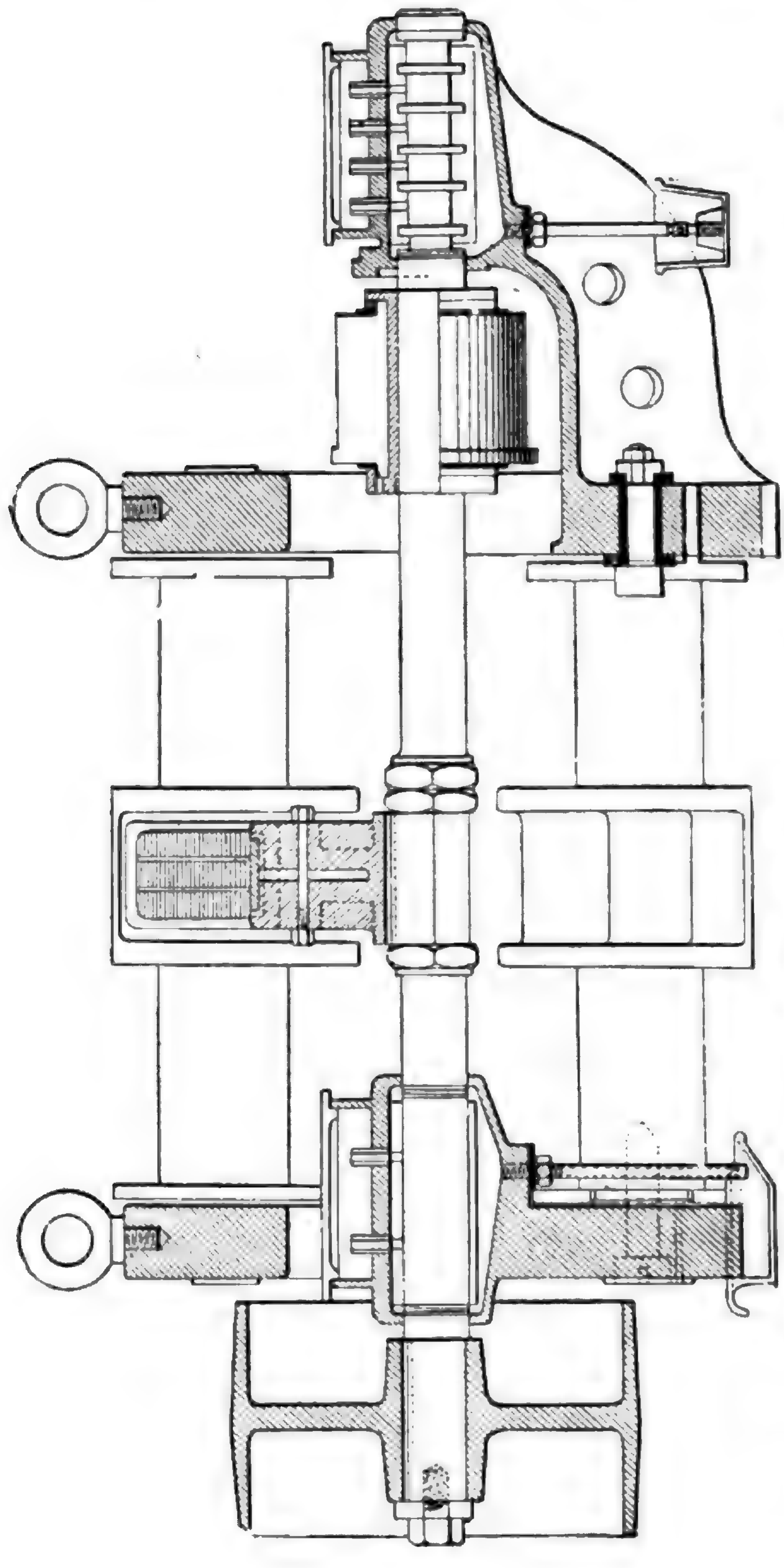


Fig. 283.—Mordey-Victoria 18 Kilowatt Dynamo (showing Section and Method of Mounting the Ring).

by lock-nuts. Square wire is used for winding the armature coils, and as they do not cover the entire external periphery of the armature core, there is ample ventilation. The winding is of one continuous wire, and the crossings are effected at the outer periphery. End-play is prevented by the use

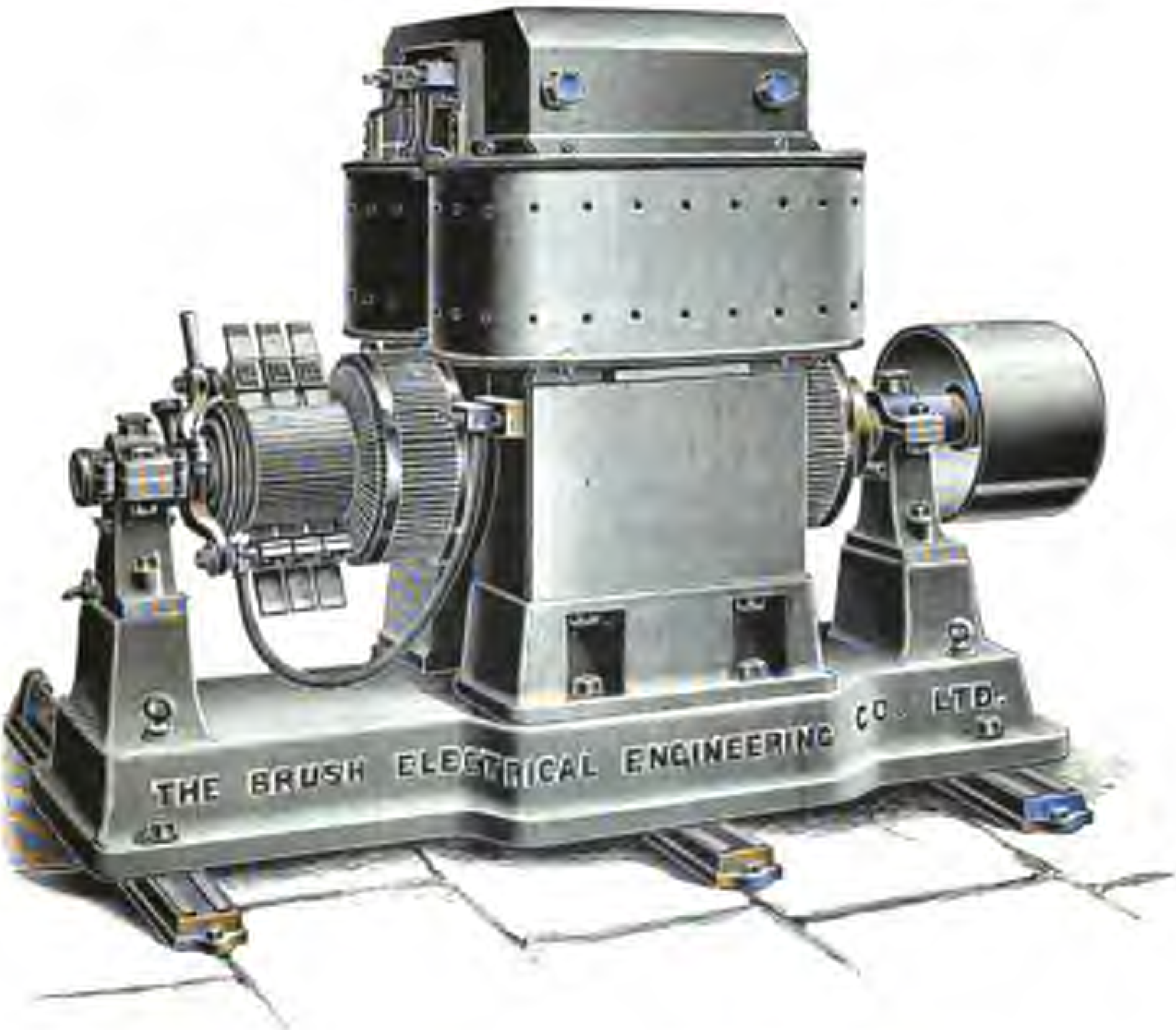


FIG. 284.—BIPOLAR DYNAMO (Brush-Falcon Type).

at one end of a deeply-grooved Babbitt-metal thrust-bearing. Mr. Mordey, as mentioned in Chapter XII., reduced the number of brushes to two, by the device of cross-connecting. Such machines are now guaranteed under tender to run at a commercial efficiency of 92 per cent.

A larger type of Victoria machine, having six poles alternately N. and S. set round the ring, was illustrated in earlier editions of

this work. As each segment of the collector is connected with those situated at 120° and 240° distance round the set, only two brushes are required.

The advantage originally claimed for the flat-ring construction, that it allows less of the total length of wire to remain "idle" on the inner side of the ring, is rather imaginary than real, for the total resistance of the armature is but a small fraction of the whole resistance of the circuit; and it is possible to spread the field so as to make all parts of the wire active without any gain whatever, if by this spreading there is no increase on the whole in the total number of lines of force in the field. The real reasons in favour of multipolar flat-ring armatures appear to be the following:—First, their excellent ventilation; second, their freedom from liability to be injured by the flying out of the coils at high speeds; third, their low resistance, due to the fact that the separate sections are cross-connected, either at the brushes, or in the ring itself, in parallel.

For outputs from 11 to 270 kilowatts the Brush Co. manufactures bipolar machines of the under-type, having drum-wound bar armatures with evolute end connectors. These machines have forged magnets; their magnetizing coils being protected by a lagging of sheet steel. For equal output they take less floor-space than the 4-pole type, though in some other respects they are less advantageous. Their general aspect is shown in Fig. 284.

Mather and Platt's Dynamos:—Figs. 285 and 286 illustrate the "Manchester" dynamo, designed by Dr. E. Hopkinson. Its compact field-magnet has cylindrical wrought-iron cores, and massive cast-iron yokes. The armature is a modified Gramme, with low resistance and careful ventilation. The commutator consists of 40 bars of toughened brass insulated with mica. It is usual in these machines so to shape the pole-pieces that there is a smaller clearance opposite the highest and lowest points of the armature; this concentrates the magnetic field and helps to prevent its distortion by the armature current. In a 24-unit machine (designed for 300 lamps) of this pattern the armature cores are 12 inches long and 12 inches in diameter, with 120 turns of wire. The resistances are: armature, 0·023 ohm; shunt, 19·36 ohms; series coil, 0·012 ohm. With a speed of 1050 revolutions per

minute the current was 220 amperes, the machine being nearly self-regulating for 111 volts; its efficiency is 90·9 per cent.[1]

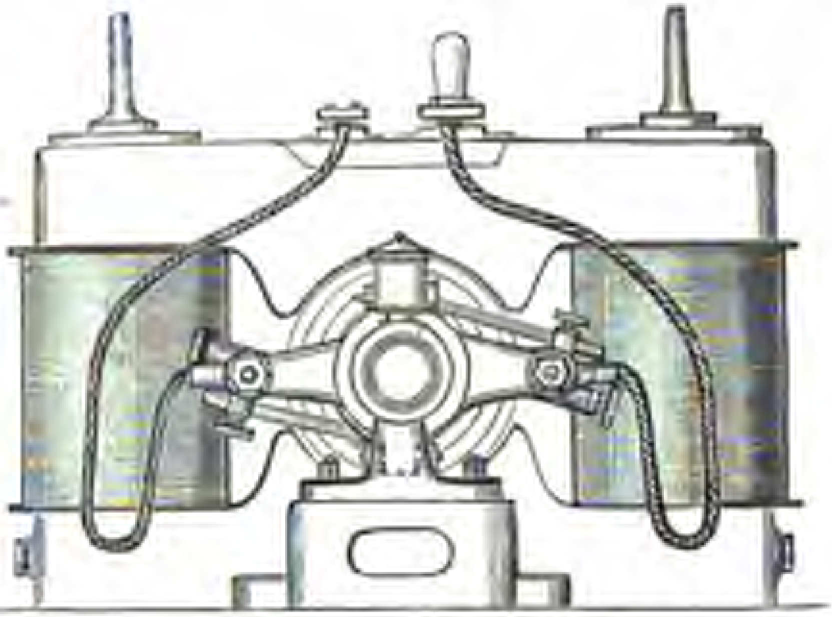


FIG. 285.—"MANCHESTER" DYNAMO (End Elevation).

Messrs. Mather and Platt also manufacture the Edison-Hopkinson dynamos depicted in Fig. 287. Dr. J. Hopkinson improved the original bipolar Edison machine by making

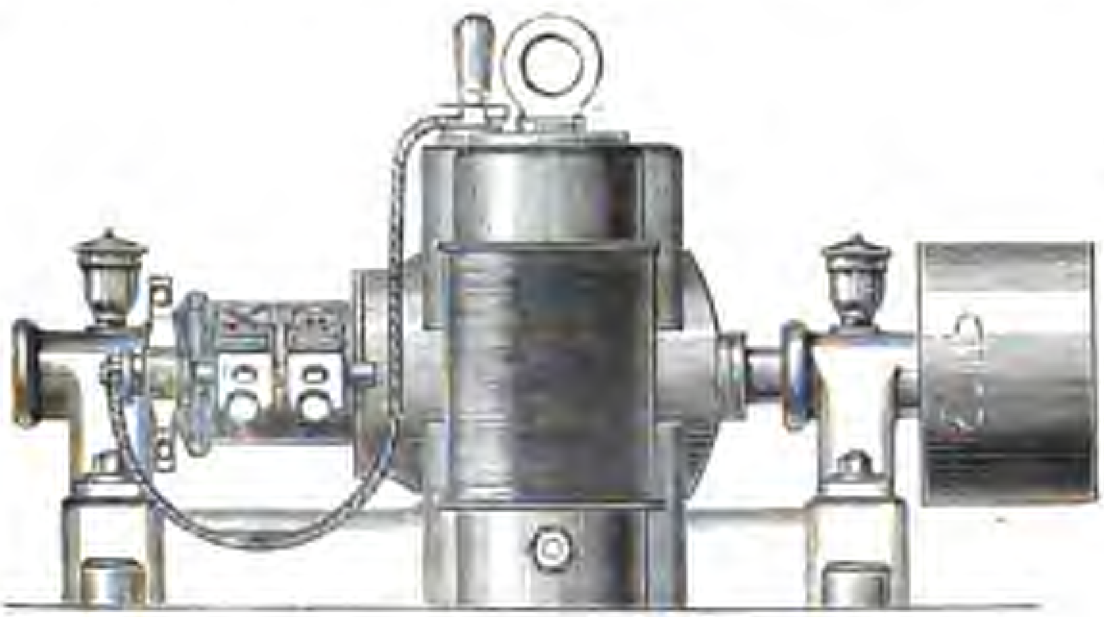


FIG. 286.—"MANCHESTER" DYNAMO (Front Elevation).

the magnetic circuit more compact, and by reconstructing the armature with cores of larger section and better mechanical

[1] One of these machines is very fully described in the paper by Drs. J. and E. Hopkinson in the *Phil. Trans.* for 1886.

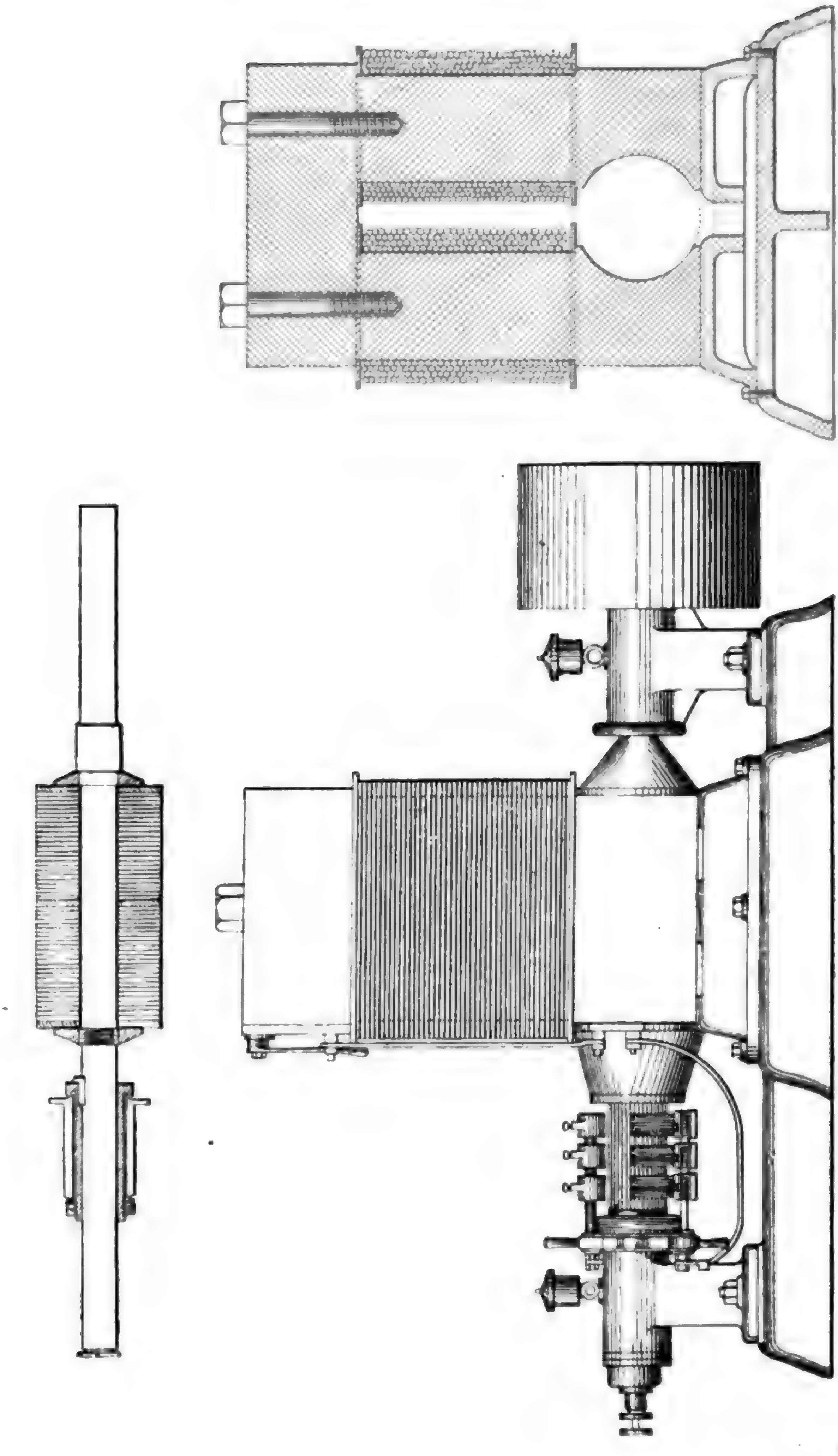


FIG. 287.—EDISON-HOPKINSON DYNAMO: ELEVATION, SECTION, AND SECTION OF ARMATURE.

construction. In the older construction, the bolts and their attached end-pieces furnished a circuit in which idle currents were constantly running wastefully round, with consequent heating and loss. Dr. Hopkinson also introduced the improvement of winding the magnets with a copper wire of square section, wrapped in insulating tape. This wire packs more closely round the iron cores than an ordinary round wire.

A remarkably complete account of one of these dynamos, constructed by Messrs. Mather and Platt, was published in 1886.[1] As this machine is often referred to in the theoretical chapters of this book, a detailed account of it is important. Its design may be gathered from Fig. 287.

The machine described is intended for a normal output of 320 amperes at a pressure of 105 volts, running at 750 revolutions per minute. The field-magnet consists of two limbs connected by a yoke of rectangular section. Each limb, together with its pole-piece, is formed of a single forging. The wrought iron used for these and the yoke is of annealed hammered scrap; the magnetic properties being those described in Chapter IV. The section of the limbs is nearly rectangular, with rounded corners. The yoke is bolted to the limbs, the joints being well surfaced. The bed-plate is of iron, a zinc base 12·7 cm. high being interposed. The armature core is built up of about 1000 thin plates of soft wrought iron, insulated from the shaft, and separated by paper from one another. They are held between two end-plates, one of which is secured by a washer shrunk on the shaft, and the other by a screw-nut and lock-nut.

The following are the dimensions of the iron parts:—Diameter of armature core, 24·4 cm.; of internal hole, 7·62 cm.; of shaft, 6·98 cm.; length of core, 50·8 cm. Length of field-magnet limb, 45·7 cm.; breadth, 22·1 cm.; width (parallel to shaft), 44·45 cm. Length of yoke, 61·6 cm.; width, 48·3 cm.; depth, 23·2 cm. Diameter of bore of field-magnets, 27·5 cm.; depth of pole-piece, 25·4 cm.; width (parallel to shaft), 48·3 cm.; width between pole-pieces, 12·7 cm. Area of section of iron in armature core, 810 sq. cm. Angle subtended by bored face of pole-pieces, 129°. Actual area of pole-piece, 1513 sq. cm.,

---

[1] See paper on *Dynamo-electric Machinery*, by Drs. J. and E. Hopkinson, in the *Philosophical Transactions* for 1886, Part I. This most valuable paper was reprinted, but without the plates, in the *Electrical Review*, vol. xviii. 1886. It was also printed in the *Electrician*, xviii. 39, 63, 86, and 175, in issues of Nov. 19th and 26th, and Dec. 3rd and 31st, 1886, where the figures of the plates are printed in the text. It is reprinted in Dr. Hopkinson's book.

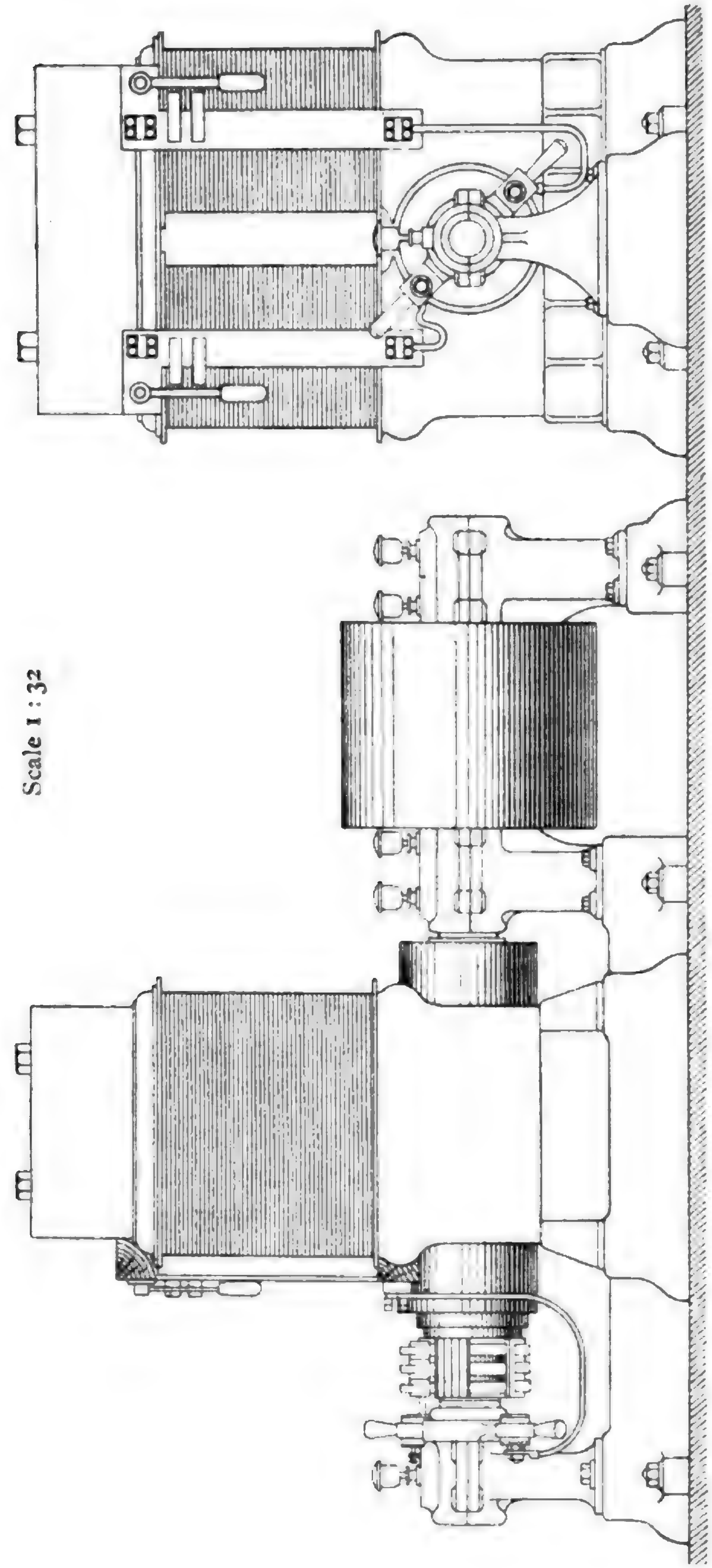
effective area, 1600 sq. cm. Thickness of gap space, 1·5 cm. Area of section of limbs, 980 sq. cm.; ditto of yoke, 1120 sq. cm.

The windings are as follows:—Magnetizing coils, 11 layers on each limb of copper wire, 2·413 mm. diameter. Total convolutions, 3260; total length, 4570 metres. Armature, 40 convolutions in two layers of 20 convolutions of stranded copper wire, consisting of 16 strands of wire 1·753 mm. diameter. Resistance (at 13·5° C.): field-magnet, 16·93 ohms; armature, 0·0009947 ohm. Normal magnetizing current, 6 amperes. Commutator, 40 copper bars insulated with mica. (Further data are given on p. 354.)

Recent tests with Edison-Hopkinson dynamos constructed by Messrs. Mather and Platt, of Manchester, show that they have an economic coefficient of over 95 per cent., and an actual commercial efficiency of over 93 per cent. These machines have usually from two to five separate brushes at either side, capable of separate removal, so that they may be trimmed without stopping the machine. In order to bring the neutral points of the commutator to convenient positions right and left, the connecting pieces which join the commutator bars to the armature windings are carried spirally through about 90°. The makers of these machines have modified in detail the winding of the armature,[1] enabling them to use copper bars instead of stranded wire. They shape the pole-pieces to diminish distortion of field, and connect the armature bars across the ends of the armature by evolute spiral connectors in two layers, like those used in Siemens' electroplating dynamos.

Figs. 288 and 289 depict the large 225 kilowatt dynamos built by Messrs. Mather and Platt for the South London Electric Railway. They are further shown in Plate IX. They have a maximum output of 450 amperes at 500 volts when running at 500 revolutions per minute. The limbs and yoke are of wrought iron, the polar masses of cast iron. The armature conductors are copper bars, and the resistance from brush to brush is 0·017 ohm. That of the shunt coil is 96 ohms, of the series coil 0·015 ohm. The compound winding is not, however, of much service for such rapidly varying loads as occur in railway work, for with such massive magnets changes of magnetism cannot take place rapidly enough; and the slow-speed engines do not govern rapidly enough. The

[1] See *Industries*, ii. 549, 1887; and Specification of Patent, 4884 of 1886.



FIGS. 288, 289.—EDISON-HOPKINSON GENERATORS AT CITY AND SOUTH LONDON ELECTRIC RAILWAY.

weight of magnets and pole-pieces is 8·5 tons, that of the yoke 3·05 tons, of the armature 2·85 tons; whilst each complete machine with its bed-plate weighs 17 tons.

For railway and tramway work, Messrs. Mather and Platt now use shunt-wound generators with a stationary battery of accumulators which by discharge relieve the generating plant at the periods of excessive load, and absorb the surplus power at periods of light load, thus securing a perfectly steady load on the generators. This system has been adopted by Dr. Hopkinson on the Douglas and Laxey electric tramway, with the result that the load on the generators is perfectly steady.

Some efficiency tests of a 53 kilowatt compound-wound Edison-Hopkinson dynamo direct-driven at 430 revolutions per minute by a Willans engine have been published.[1] Indicated horse-power absorbed 85·3; output 475 amperes at 110 volts, or 52·2 kilowatts, or 70·0 H.P.; making a net efficiency of 83·3 per cent. The electrical losses were only 3 per cent., whilst 10 per cent. was lost in friction in engine and dynamo.

Independent efficiency tests have recently been made on some large dynamos of the Edison-Hopkinson type, constructed by Messrs. Mather and Platt for the Manchester Corporation. These machines are wound for an output of 590 amperes, at 410 volts, at 400 revolutions per minute, and were tested by Hopkinson's method (Chap. XXX.), being coupled together as generator and motor with the loss in the combination being supplied by a third independently driven machine, coupled in series with the two armatures, so that all the measurements were electrical. The resistances of the shunt coils are 52·7 ohms and of the armatures ·01167 ohms. The losses in percentages of the power absorbed were:—

		Per cent.
In armature	=	1·56
In shunt coils	=	1·22
Hence, electrical efficiency	=	97·22
Loss in friction of bearings, eddy currents, hysteresis, and friction of brushes..	=	2·11
Hence commercial efficiency, including all losses	=	95·11

[1] *The Electrician*, xxv. 707, 1890.

Messrs. Mather and Platt also construct a multipolar type of machine, with the armature built up after the manner of their "Manchester" machine, but with drum evolute winding. The winding is developed, either with the convolutions wound zigzag, so as to bring the effect of all the poles in series, or with the convolutions coupled in parallel. In either case the bars of the armature, in alternate gaps, are at approximately the same potential, so that there are as many points of commutation as poles, and the brushes in alternate gaps can all be coupled parallel. The first winding is particularly suitable for slow-speed high-potential machines of large output, while the second is useful for machines of low potential and large current, such as are frequently required for electrolytic purposes.

Edison Co.'s Dynamos.—In 1879, after proposing a strange sort of machine as generator, in which inductive coils were waved to and fro at the end of the prongs of a gigantic tuning-fork, Mr. Edison, with the assistance of Mr. Upton, designed the bipolar machine which was depicted in former editions of this work. It had a drum-armature rotating between heavy pole-pieces excited by a very long magnet with tall columnar limbs.

In the larger machines two or three tall field-magnets were assembled side by side, over an armature of double or triple length. An Edison 60-light "Z" machine of the older pattern, tested by the Committee of the Munich Exhibition, was found to give an efficiency, which, if measured by the ratio of external electric work to total electric work, exceeded 87 per cent.; but its commercial efficiency—the ratio of external electric work to mechanical energy imparted at the belt—was only, at the most, 58·7 per cent. This was due to the production of wasteful eddy-currents in the bolts which held together the armature and other masses of metal. The "Jumbo" steam dynamos were even less efficient, and required a 4 H.P. fan to be attached to the armature shaft to keep them cool by a forced draught of air.

Dr. J. Hopkinson's efforts to improve this machine resulted, as detailed on p. 420, in a better design.

The field-magnets of all the larger machines turned out by Edison prior to 1884 had a number of long iron columns as cores to receive the coils. Since that date the more compact arrangement of a single magnetic circuit with short stout magnets has been adopted by the Edison companies on both sides of the Atlantic. The usual form (type of 1888) of Edison dynamo, as used in the States, is depicted in Fig. 290. The field-magnets are of cast iron, with a massive yoke, and stand upon a high footstep of zinc to diminish short-circuiting through the bed-plate. These machines are shunt-wound, and

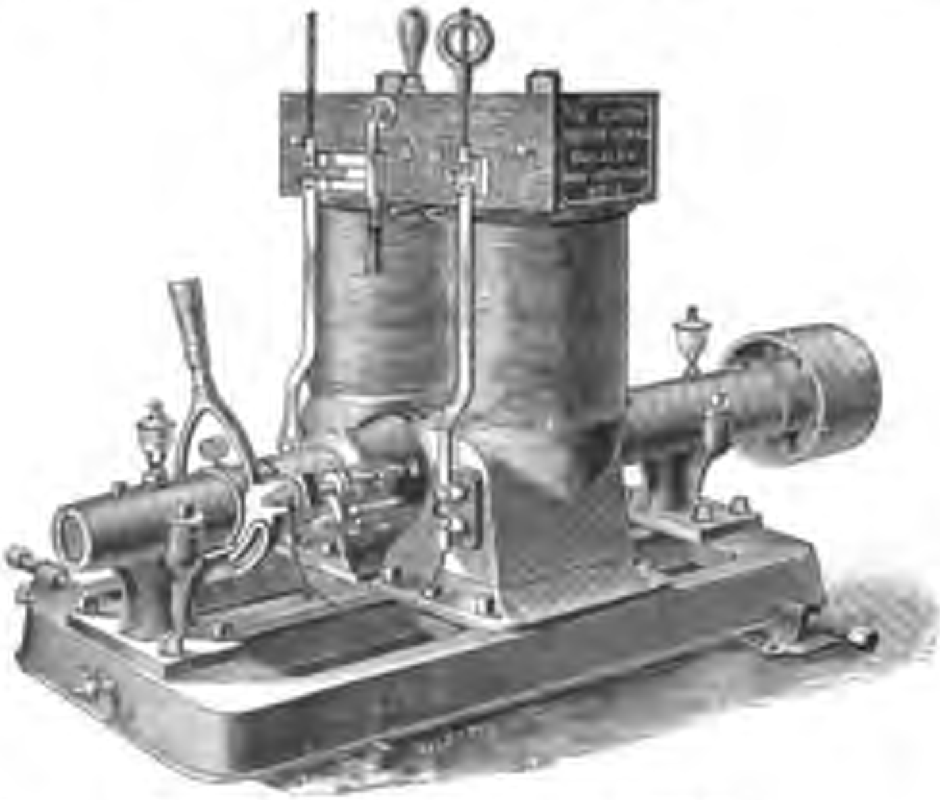


FIG. 290.—EDISON DYNAMO (1888 Type).

are intended for incandescent lighting work. The bearings are longer and the mechanical arrangements in every way superior to those of the older machines.

At the Paris Exhibition of 1889 were a number of these bipolar dynamos built by the Edison Machine Company, of Schenectady, ranging from a small 2½ kilowatt machine, 30 inches high, to one of 150 kilowatts, 8 feet 6½ inches high. Drawings of the largest machine are given in Plate V. This dynamo is capable of supplying 1075 amperes at 125 volts, when running at 450 revolutions per minute. It has a 41-part commutator and a 41-bar armature. There are six brushes

in each set, each 1·88 inches wide and about 0·62 inches thick. Its weight is 12½ tons.

Some particulars published in 1890 by M. Minet[1] concerning some of these dynamos show that the mean value of B in the gap space was from 3200 to 4100. The electrical efficiency of the larger machines was 93·8; the nett efficiency about 89·7 per cent.

Though this bipolar type has now been abandoned, some statistical information may be valuable as showing the relations which have been found to give good results in machines of very different sizes: see following pages.

As these machines were of exceedingly good construction some details respecting the precautions taken to insulate the magnet-windings will be of interest. The ordinary machines working at 100 to 125 volts are insulated as follows:—End-rings of hard rubber are wedged upon the iron cores with mica. When bits of sheet mica are used, these are cut to be 1½ inch wide and at least 3 inches long; but when "made mica" sheets are used, long strips 3 inches wide are cut, and conformed by heating to the curvature of the core. In either case the mica projects at least 1 inch on the inner side of the ring. Then over the core is laid one layer of varnished muslin 24 mils thick, cut to the exact width between the end-rings. Upon this are placed two layers of plain pressed board 20 mils thick, cut one inch wider than the width between the end-rings, and serrated with V-cuts ½ inch deep at its edges, so as to allow these edges to make flanges against the end-rings, the serrations of the two layers breaking joint one with the other. The total thickness of core-insulation is thus 64 mils. A core-paper is laid between every four layers of winding. Between series and shunt coils, in compound-wound machines there is as careful an insulation as on the cores. When the winding is completed two layers of pressed board are laid over, and served with an external winding of hard rope, and varnished.

For machines up to 250 volts, 4 layers of oiled pressed board are used over the muslin.

[1] *La Lumière Électrique*, 1890, xxxv. 401.

PARTICULARS OF ARMATURE OF 125 VOLT DRUM-WOUND BIPOLAR MACHINES.

Output in Kilowatts.	Amperes.	Speed, Revs. per Min.	Peripheral Speed of Armature. Feet per Sec.	Diameter of Iron Body of Armature in Inches.	Radial Depth of Iron Core in Inches.	Radial Depth of Winding.	Length of Iron Core in Inches.	Flux-density. Lines per sq. cm.	Total Flux through Armature.	Number of Parts in Commutator.
2·5	20	1900	38	$4\frac{1}{2}$	2	·34	8·5	9,000	787,000	44
5	40	1800	45	$5\frac{11}{16}$	2·25	·47	9·75	8,200	1,241,000	58
7·5	60	1700	45	$5\frac{7}{8}$	2·4	·5	10·75	10,500	1,583,000	48
10	80	1600	44	$6\frac{1}{4}$	2·6	·44	12	12,400	2,410,000	50
15	120	1500	44	$6\frac{3}{4}$	2·8	·5	13·5	12,100	2,686,000	48
20	160	1400	49	$7\frac{3}{4}$	3·0	·56	15	11,600	3,429,000	66
25	200	1300	50	$8\frac{3}{4}$	3·0	·5	16	12,700	4,558,000	66
30	240	1200	48	$9\frac{7}{16}$	3·25	·56	17·5	14,400	5,501,000	58
40	320	1000	49	$11\frac{1}{16}$	4·5	·59	20·5	12,350	7,386,000	52
50	400	700	41	$12\frac{15}{16}$	4·5	·46	24	11,750	11,030,000	50
80	575	650	47	$16\frac{3}{8}$	6·0	·62	25	10,720	13,750,000	48
150	1075	450	50	$23\frac{3}{8}$	9·0	·75	25	8,225	21,980,000	41

MAGNET DATA. STANDARD BIPOLAR MACHINES (125 VOLTS), SHUNT-WOUND.

Kilowatts	Mean Diameter of Helix of Wire on Core in Inches.	Length of Wire (calculated) on both Cores in Feet.	Number of Turns.	Resistance in Ohms.	Radiating Surface in Square Inches.	Maximum Watts in Cores, with all extra Resistance out.	Watts per Square Inch of Radiating Surface.
2·5	5·94	10,325	6644	123	524	94·33	0·18
5	6·8	9,000	5051	62	609	159·5	0·262
7·5	7·7	10,560	5230	51	935	177·2	0·19
10	8·8	11,780	5120	42	1190	185·5	0·156
15	9·5	14,000	4830	51	1361	202·5	0·149
20	10·6	15,000	5640	23	1480	268	0·180
25	11·3	15,000	5400	43	1860	258	0·138
30	12·25	14,850	4630	34	2075	339	0·163
40	13·9	14,850	4075	25	2790	439	0·157
50	16·13	17,000	4010	23	3620	469·5	0·137
80	19	18,800	3760	17	4550	682	0·150
150	23·5	18,300	2980	6·7	7200	995	0·138

For machines up to 500 volts or more, 3 layers of oiled linen 5 mils thick, not turned up at edges, are placed over the muslin. Over these come first 4 layers of oiled pressed board, and then 2 layers of plain pressed board, the latter with edges serrated to form flanges. This makes a total thickness of insulation 159 mils. Core-papers are laid between every 3 layers of winding, and three layers of pressed board are served on the outside.

The armatures are equally carefully constructed. The core-disks, 12 mils thick, are assembled in "sections" con-consisting of 5 disks with 11 sheets of paper; a sufficient number of sections being taken to make up the required "body." The body is held together with insulated bolts, each enclosed in a paper sleeve; the core-sections being compressed by hydraulic forces varying from 30 to 200 tons. Both body and shaft are insulated with a coating of japan, several layers of oiled paper, and a layer or two of tape. Stout iron

end-plates, securely keyed to the shaft, and nicked to receive driving pegs of fibre, are provided, with one or two similar plates at the middle of the core; while headings of varnished muslin or canvas protect the ends of the core from contact with the windings.

General Electric Co.'s Dynamos.—At the Schenectady works the bipolar Edison type of dynamos has been superseded by multipolar types. Fig. 291 gives a general view of a 60 kilowatt machine of the standard type now adopted for the sizes under 100 kilowatts, having 4 poles. The magnet cores and yoke are of special mild steel soft castings. The windings of the armature are sunk between teeth in the core-

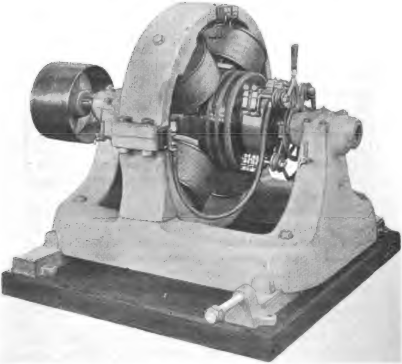


FIG. 291.—GENERAL ELECTRIC CO.'S MULTIPOLAR DYNAMO.

disks, with air-ducts at intervals. The insulation consists of alternate laminations of sheet mica and tough paper. A temperature rise of 40° C. is permitted unless a lower limit is stipulated for.

Fig. 292 gives a view of a 6-pole street-tramway generator of 400 kilowatts at 150 revolutions per minute. The output is

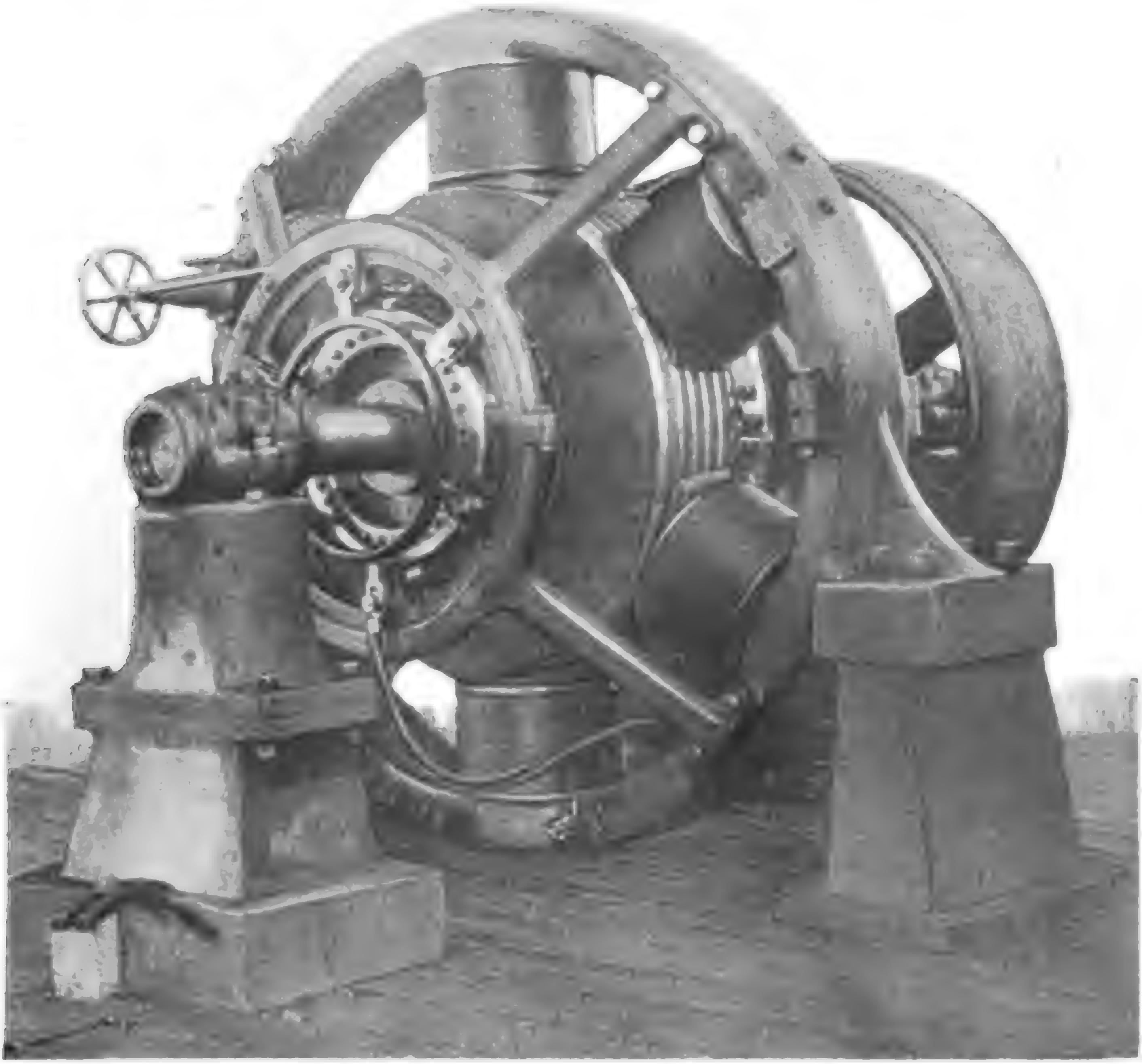


FIG. 292.—GENERAL ELECTRIC CO.'S STREET-TRAMWAY GENERATOR.

800 amperes at 500 volts. These machines are so designed that the flux-density shall be 85,000 lines per square inch in the pole-cores, 70 000 in the yoke. In the armature disks the density is also 70,000 lines per square inch, increased to 135,000 in the core-teeth, this high degree of saturation being

preferred as helping to prevent distortion of field. The permitted amperage in the armature conductors is only 1500 amperes per square inch. Some much larger machines have been constructed for direct-driving, as, for example, the six 1500 kilowatt machines in the Brooklyn generating station.

Parshall's Multipolar Dynamos.—Mr. H. F. Parshall, who advised the General Electric Co. in the development of their multipolar generators, has kindly furnished the data for the design shown in Plates X. and XI. This represents a recent 6-pole, 150 kilowatt, machine with cylinder drum-armature, giving 300 amperes at 525 volts at 200 revolutions per minute. The core-disks are slotted with 154 teeth, between which lie the conductors in two layers. To diminish sparking a duplex winding (p. 272) is adopted, so that in each slot there are 4 conductors, and in the commutator 308 parts. The mode of construction of the latter, which is peculiarly substantial, is shown in Plate XI. It will be noted that the armature core-disks, built up of overlapping segments, have internal lugs by which they are bolted together and driven upon a grooved spider. There are about 10,000 ampere-turns of excitation upon each pole, of which about 4000 are provided by the compounding coils at full load. The shunt coil has to provide for 5815 ampere-turns which are required as follows:—4350 to drive the flux across the gap-space, 645 for the yoke, 450 for the pole-core, 300 for the teeth, and 70 for the armature body. The flux through each pole is 8,700,000 lines.

Goolden's Dynamos.—Excellent dynamos have long been manufactured by Goolden & Co. (now merged in the firm of Easton, Anderson and Goolden), the chief designer having been Mr. Ravenshaw. In their larger dynamos bar armatures are employed, having rectangular conductors built up of laminated or twisted copper strip, lightly oiled. The smaller are wound with round wire, silk covered. Amongst their features are swivel bearings and screw-fed brushes. In Fig. 293 is illustrated a 61 kilowatt Goolden dynamo of the over-type, direct-driven at 460 revolutions per minute by a Willans engine, a combination frequent in central lighting

stations in England. The magnet limbs and pole-pieces are of wrought iron. The pole-faces are bored elliptically, so as to leave greater air-space below armature than above, and counteract magnetic pull. The conductor bars are driven by

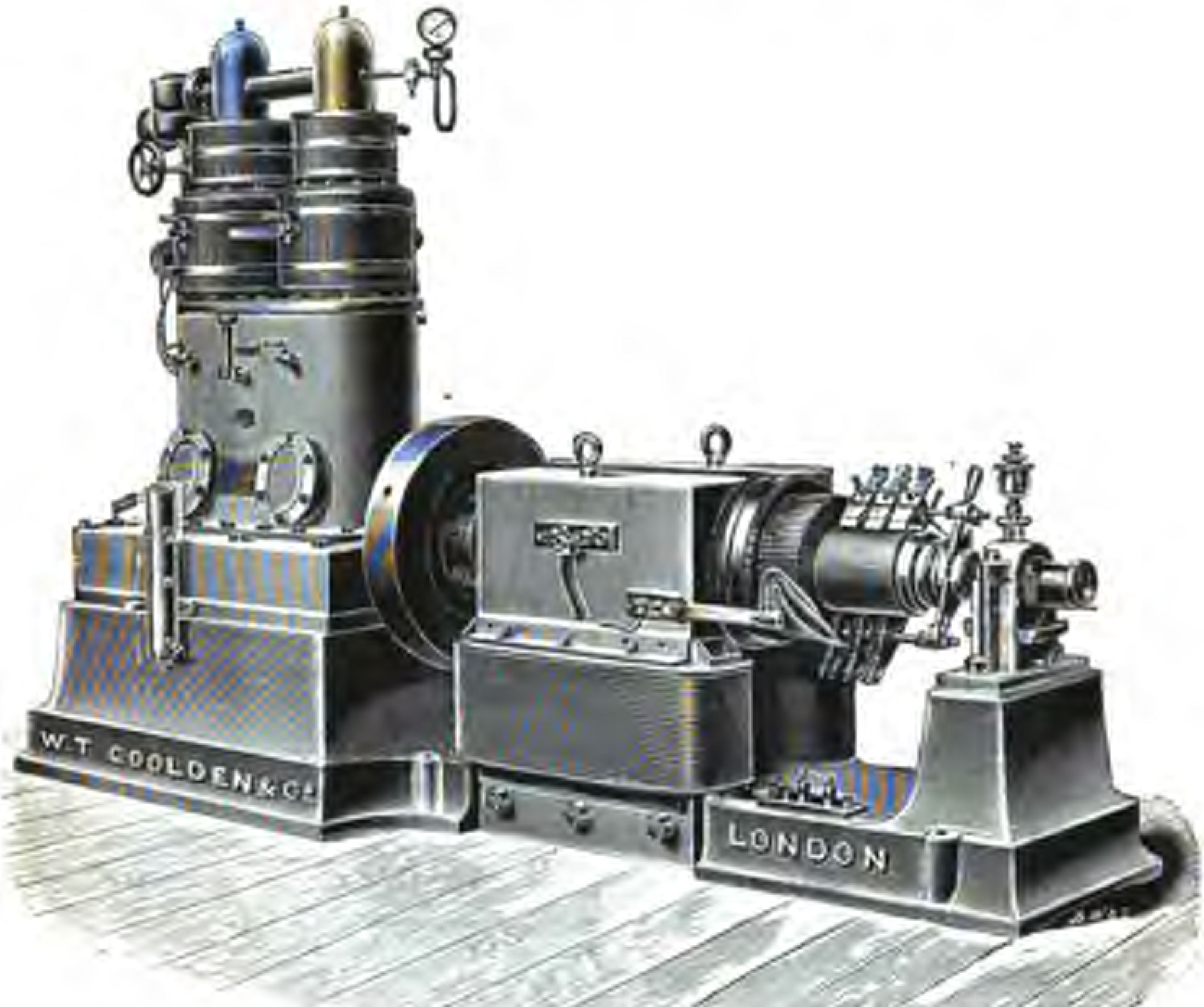


FIG. 293.—GOOLDEN DYNAMO AND WILLANS ENGINE.

80–100 fibre horns inserted in key-ways in the periphery of the core: they are united at ends by stamped evolute connectors. At one end the bars are made fast to the segments of the commutator; at the other they are supported by an insulated brass ring, which allows them to expand longitudinally when they warm up. The commutator is of hard-drawn copper and mica, built up on a separate sleeve keyed to the shaft. The following tests were made of one of these

combined plants, running at 500 revolutions per minute, showing the location of the various losses :—

	At Full Load.			At Half Load.		
Net output (watts)	..	50,000	..	..	25,000	
Loss in armature resistance	1,010	..	..	250		
Loss in magnet coils	615	..	..	590		
Loss by friction, eddy-currents, and hysteresis	255	..	..	255		
Total loss in dynamo	1,880	.. 1,880	..	1,095	1,095	
Gross output	..	51,880	.. 51,880	..	26,095	26,095
Loss in engine	..	..	5,920	..	..	5,920
Total indicated H.P. in watts ..	..	..	57,800	..	..	32,015
Commercial efficiency of dynamo ..	96·2 per cent.			95·7 per cent.		
Commercial efficiency of combination	86·5 ,,			71·8 ,,		

Holmes' Dynamos.—Messrs. J. H. Holmes & Co., of Newcastle-on-Tyne, manufacture the "Castle" dynamo, a compact and well-built type of machine. The larger machines are drum-wound. The armature core is made up of thin plates of charcoal iron. The commutator bars are forced together by hydraulic pressure before being clamped up. Some elaborate tests by Professor Kennedy on a 123 kilowatt machine, described in Chapter XXX., showed a nett efficiency of 95·6 per cent. Messrs. Holmes have applied themselves very successfully to the problem of obtaining a constant pressure from a dynamo when driven at variable speeds.[1] The case in which this arises is in the lighting of railway trains by dynamos driven from the axles of one of the carriages. This they accomplished by a special combination of two dynamos, together with certain automatic switches. The larger dynamo is wound with two

[1] For various solutions of this problem see following Specifications of Patents: 342 of 1889 (Mordey); 3420 of 1889 (Sayers); and 20,244 of 1889 (Holmes).

circuits upon the field-magnets, and its shaft is coupled to a smaller dynamo, the function of which is to send a demagnetizing current around the second circuit of the larger dynamo,

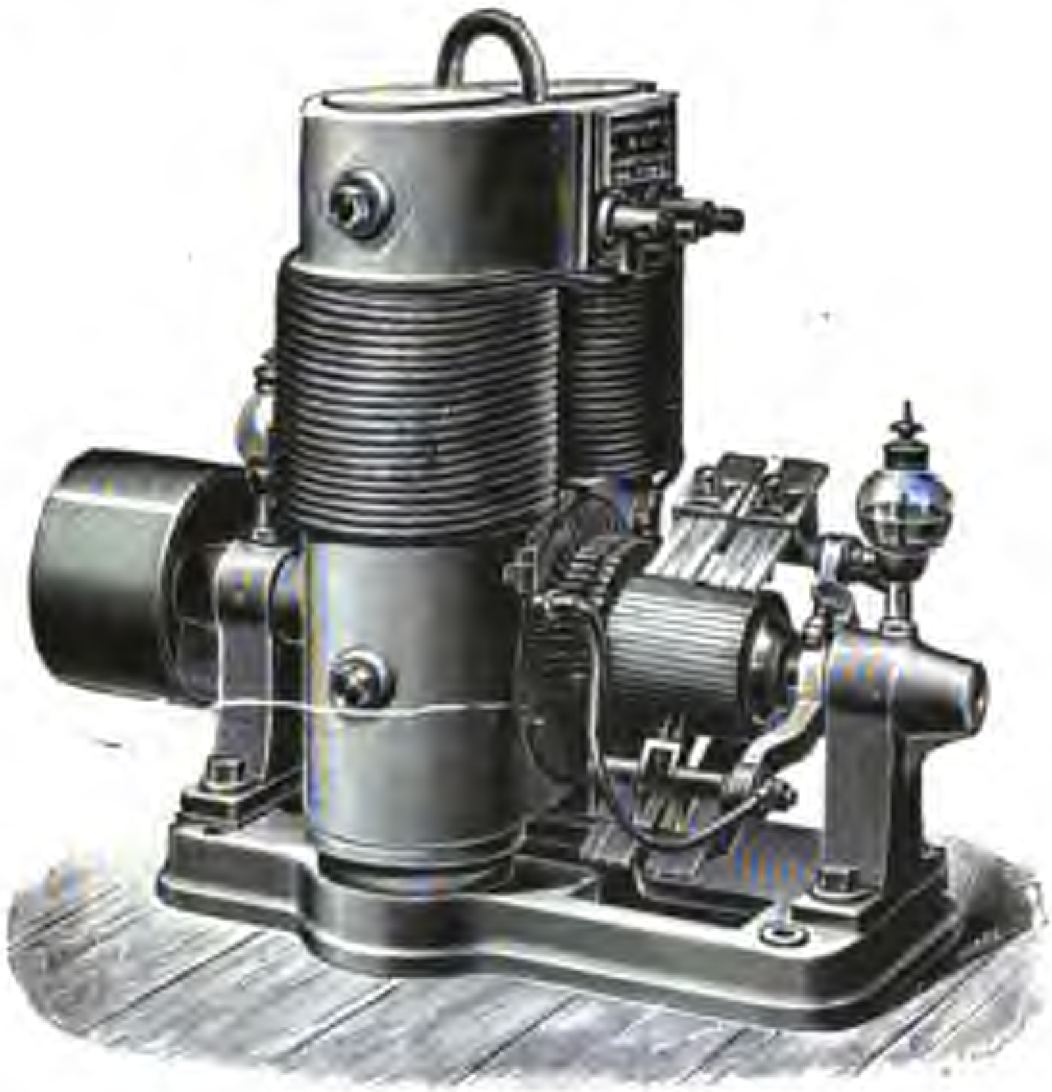


FIG. 294.—HOLMES' DYNAMO.

so that as the speed rises its magnetism falls nearly in proportion. By this means the voltage is kept nearly constant, though the speed of the train may vary from 30 to 70 miles per hour.

Parker's Dynamos.—Mr. Parker of Wolverhampton (formerly of the Electric Construction Corporation) has introduced a useful detail into the construction of the well-known bipolar type, in making the pole-pieces jointed, so that the armature can be lifted straight off its bearings instead of being drawn out horizontally. In Fig. 295 the construction with hinges is shown. For bipolar machines of the "under" type, the lower halves of the polar masses are fixed in the bed-plate, and the main body of the magnet is lowered upon them after the

armature is in place. Mr. Parker uses the Eickemeyer method (see p. 310) of forming the coils both for bipolar and multipolar armatures, and prefers this construction to the use of bars. By using Eickemeyer coils for large-current armatures the number of soldered joints is diminished, and at the same time complete mechanical and electrical balance is assured. Smooth cores only are used. Mica insulation is used between the bars of the commutator, the end washers being either of micanite or of red fibre covered with mica.

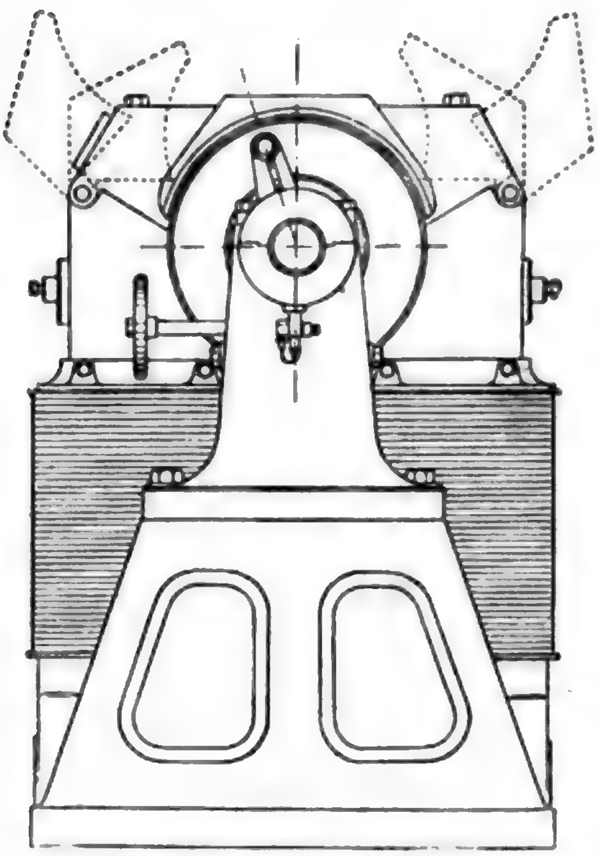


Fig. 295.—Parker's Bipolar Dynamo, with Jointed Poles.

Mavor and Coulson's Dynamos.—This firm constructs dynamos on Sayers' patents, with the compensating armature devices described on p. 395. Plate XII. depicts a 34 kilowatt bipolar generator intended for power-transmission. Its armature has core-disks with 108 teeth, and the main winding consists of 216 convolutions or 432 conductors, 4 in each slot. The commutator has 54 segments, and there are 54 "commuting coils," each of 3 turns embracing each a span of 7 teeth. The main windings have a sectional area of 0·025 sq. inches, and those of the commuting coils 0·0072 sq. inches. The magnet winding carries 0·8 ampere with 25,300 turns, having a (hot) resistance of about 560 ohms. The armature core is 17½ inches long by 9½ inches in diameter. The magnets are of mild cast steel, to carry a useful flux of 8,000,000 lines. The values of $\mathfrak{B}$ are as follows:—In air-gap, 7100; in armature body, 12,400; in the teeth, 15,400; in the magnet cores, 13,600; and in the limbs, 10,700. The complete armature weighs 985 lbs., the magnet and bed-plate complete, 2386 lbs.

Sayers' winding enables these machines to give constant

pressure at all loads without compound winding on the magnets; and by careful disposition of the reversing poles the makers have succeeded in attaining the long-sought result of fixing once for all the position of the brushes. The lead remains fixed and the running sparkless, even up to an overload of 75 per cent. above the full normal output; and this while using ordinary copper gauze brushes, not with carbon brushes, which cause more heating of the commutator. This

FIG. 296.—PHŒNIX DYNAMO (1887 Type).

particular dynamo gives 75 amperes at 450 volts when running at 800 revolutions per minute. The bearings, which are swivelled to render them self-centering, closely resemble Fig. 255, p. 334.

Paterson and Cooper's Dynamo.—The "Phœnix" dynamo, constructed by Messrs. Paterson and Cooper, from the designs of Mr. W. B. Esson, has also a modified cylindrical ring-armature, built up of a number of very thin rings of Swedish iron separated from one another by paraffined paper and

secured to two spiders by three bolts passing through indentations in the core-rings, as shown in Fig. 220, p. 291.

The machines have upright single horse-shoe magnets, in some instances made of a single wrought-iron forging slotted out to form the two limbs, and bored. The shaft is supported from two gun-metal bridge-pieces. There are generally no teeth on the armature-cores, which are made of plain washers to avoid cost of milling out the teeth. The conductors are made of stranded cable.

Fig. 296 shows a design, in which the field-magnets are cast in one piece. This machine can be made at lower cost of equal power with a lighter machine having wrought-iron magnets. In both types there is no joint in the magnetic circuit, and the magnet coils are wound upon special bobbins of sheet-iron flanged with brass, slipped on over the cores. Fig. 241, p. 314, shows the construction of the commutator.

The constructional data of a dynamo giving 90 amperes at 105 volts at 1420 revolutions per minute and full calculations of the windings, together with scale drawings, were given in the previous edition of this book.

The same makers have produced arc-light dynamos to yield 10 amperes at pressures varying from 700 to 1500 volts. The following are the data of a seven kilowatt arc-lighter, for 12 to 15 arc lamps :—

Armature core, 32·5 cm. external diameter, 22·9 cm. internal; axial length, 15 cm.; wound with 1872 turns of wire 1·2 mm. in diameter, in 48 sections of 39 turns each in three layers. Armature resistance, 3·448 ohms. Field-magnet coils, 2, of 954 turns each, in series; their total resistance, 4·541 ohms. The maximum induction in armature is 19,080, in field-magnet 10,800 lines per sq. cm. The magnets are more highly saturated and have a relatively greater weight of copper upon them than in constant-potential machines.

Schuckert's Dynamos.—The armature of the original Schuckert machine was a flat ring, the core of which was built up of a number of thin iron disks. The winding was identical with that of a Gramme machine, and the field-magnets resembled, in general, those of the typical Gramme.

The ring was almost entirely enclosed between wide pole-pieces, each of which covered nearly half the ring. The flat ring was intended to give better ventilation and employ less idle wire than the cylindrical pattern of ring. In recent years Messrs. Schuckert and Co., of Nürnberg (now known as the Elektrizitäts-Aktiengesellschaft), have brought out many modified types of machines, having the flat ring-armature, the cores being of iron tape insulated with paper, coiled upon a brass foundation ring. Only the small sizes are made with two poles, all above 12 kilowatts being multipolar. As is the case with most German dynamos, the field-magnets are of cast iron, the commutator bars are insulated with paper, and the wires secured to them by screws. At the Frankfort Exhibition of 1891 a large number of these machines were shown,[1] the finest of them being a large direct-driven multipolar of a certain capacity of 230 kilowatts, giving 1000 amperes at 230 volts, and taking 320 H.P. at 160 revolutions per minute. This machine was depicted in the previous edition of this book. The diameter of the ring is 240 cm., wound with 1120 turns of braided stranded wire. The commutator is 150 cm. in diameter, with 560 segments, cross-connected, so as to reduce the number of brushes. There are 14 poles, and the armature winding is grouped in 14 rows of 80 turns each, all in parallel. The magnet poles project inwards from an external cast-iron case, divided horizontally. There are four brush-holders, each carrying three brushes. A still larger machine with 16 poles is at work in the central station at Düsseldorf.

Lahmeyer's Dynamos.—Mr. Lahmeyer, formerly with a firm in Aachen, now chief constructor of the Elektrizitäts-Aktiengesellschaft of Frankfort, has for some years designed bipolar and multipolar dynamos[2] with inward-pointing poles, of the type originally denominated *iron-clad* by Rankin Kennedy.

[1] See article by Esson in *Electrical Review*, xxix. 526, 1891.

[2] See *Centralblatt für Elektrotechnik*, ix. 71 and 411, 1887; also *Elektrotechnische Zeitschrift*, ix. 89, 1888. For more recent forms see *Electrical Review*, xxix. 404, 1891.

Of the earlier forms the armature was wound on a plan suggested by Arnold of Riga, and independently suggested by Crompton, namely, the conductors are wound between teeth in the periphery of the core, after which the whole exterior of the armature is served with a thin layer of insulating material, and over this a layer of iron wires is wound. The official report of the Frankfort Exhibition of 1891 describes a large variety of excellent machines by this firm; one of its specialities being the manufacture of rotatory transformers for continuous and polyphase currents.

Thury's Dynamos. — M. Thury, of the Compagnie de l'Industrie Électrique, of Geneva, has long designed good dynamos. A 6-pole hollow-drum dynamo, having its field-magnet built up of tangential slabs, was illustrated in the previous edition of this work. The Company has lately constructed several large 12-pole vertical-shaft machines to be driven direct by turbines (see Fig. 297). The armature, whose diameter is 2·5 metres, revolves at a speed of 45 revs. per minute, and yields 275 amperes at 600 volts.

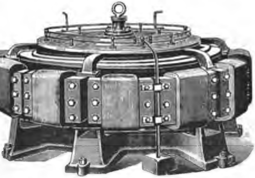


FIG. 297.—SALÈVE ELECTRIC RAILWAY DYNAMO (Thury Type).

Desroziers' Dynamos.—These multipolar dynamos with disk-armatures are in considerable use in lighting-stations in Paris, in various sizes up to 370 kilowatts. They are manufactured by the well-known house of Breguet. The theory of disk-winding has been treated in Chapter XII., and some

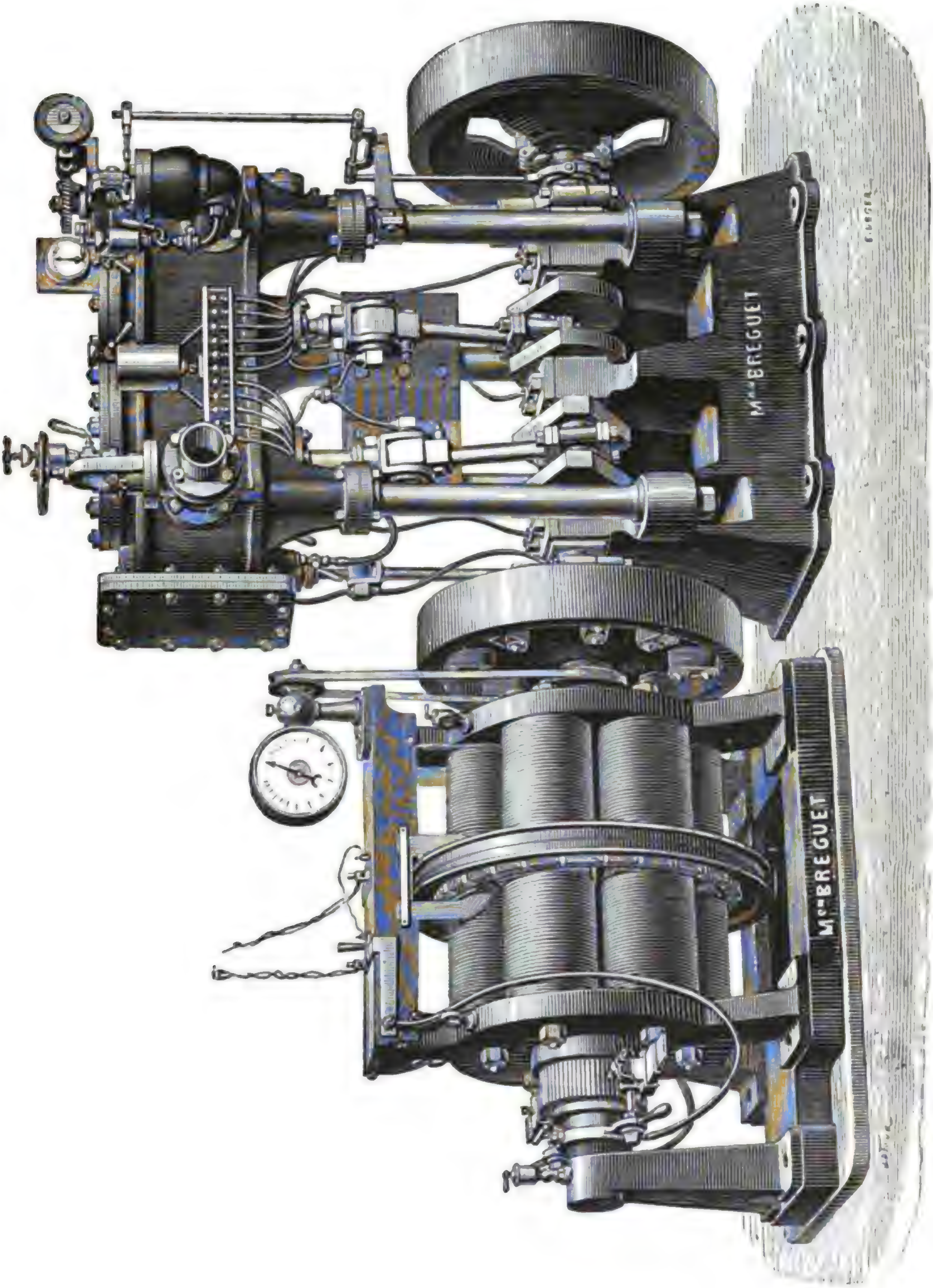


Fig. 298.—Desroziers' Disk Dynamo.

further remarks on disk-dynamos will be found on p. 43. Fig. 298 gives a view of one of these dynamos direct-driven. The armature is without iron, avoiding hysteresis losses, and is constructed as described on p. 282 in two halves, which are then joined together. A 150 kilowatt machine giving 1000 amperes at 150 volts at 150 revs. per minute had an armature 2·2 metres in diameter, weighing with its shaft 2·4 tons. The entire dynamo weighed 14·6 tons.

CHAPTER XVIII.

ARC-LIGHTING DYNAMOS.

IN cases where lighting is to be done exclusively by arc lamps in great numbers, it is usual to arrange the lamps all *in series*, even to as many as 100 to 200 lights, and to provide a dynamo-machine which will give a constant, or nearly constant, current at a sufficiently high voltage. The usual current for which arc lamps are designed is 10 amperes. Some lamps are designed, however, for 8 or 6 amperes, and some for 4 amperes. These are therefore exceptions. On the other hand, the arc lamps used for search-lights and lighthouse work are designed to take larger currents, up to 200 amperes or more. With continuous-currents arcs cannot be maintained burning steadily unless they are fed at a pressure of about 40 to 45 volts for each lamp. If the pressure is insufficient, the arcs will be unstable and give out a hissing sound. The steady arc behaves as though it exercised a counter electromotive-force of about 39 volts. When arc lamps are to be used *in parallel* with one another, the mains must have a greater difference of potential than 45 volts—55 or 60 volts is preferable—in order that additional resistances may be introduced to steady the current through each lamp. Such additional resistances are not necessary when a number of arc lamps are used *in series*, as they help to steady one another. The great advantage in the series arrangement is the saving in copper thereby effected. Alternate-current arcs only need a pressure of 30 to 33 virtual volts.

In arc-lighting in series, the function of the dynamo is to keep the amperes constant, no matter how many or few lamps are in circuit; whilst each lamp is provided with a shunt device which governs the movement of the carbons, so that

the feeding of them shall keep the length of the arc, and the volts at the terminals of the lamp, approximately constant.

We may take it, therefore, that a system of 20 arcs in series will require a dynamo giving a current of, say, 10 amperes, and a pressure, when all the lamps are in use, of nearly 1000 volts. This allows 45 volts per lamp, and 5 volts more for driving the current through the resistance of the wires between each lamp and the next.

Constant-current dynamos are also needed for the purposes of municipal lighting by means of special glow-lamps (with thick carbon wires instead of thin filaments), connected in series, so that the same unvarying current flows successively through a large number of them.

It was suggested by Deprez in 1881, that by a species of compound winding, consisting of an initial excitation and a shunt excitation combined, a dynamo might be constructed to give a constant current at constant speed. The assumption which underlay his reasoning, that the magnetism is proportional to the exciting power, is, we know, not justified except for the early and unstable stage of magnetization; all attempts to produce a practical compound winding for this purpose have therefore failed.

For the production of constant currents at such high voltages as 2000 to 3000 volts the ordinary ring and drum armatures, wound in a closed coil, in numerous sections, and provided with a commutator consisting of numerous closely-packed parallel bars, have not been found entirely satisfactory, for the commutator of this type is liable to give way under the high pressure, and to deteriorate under the action of long sparks flashing over its surface from brush to brush under the wide alterations of lead that are inseparable with this mode of working. Nevertheless, good results have been obtained by several firms (see p. 465) in the use of high voltages in machines having ordinary commutators with many segments. Experience, however, is in the main against the use of armatures of this type. More simple forms are needed that will not break down under the conditions of work. These forms are usually associated with other modes of construction in which the armature winding does not constitute a closed coil.

Open-coil Dynamos.

As explained on p. 40, it is possible to construct armatures in which the separate coils or sections of the windings are not united together in one closed circuit. An example is given in Fig. 299. This diagram (which should be compared with Fig. 33, p. 39) shows an armature consisting of two separate loops, set in planes at right angles to one another, so that when one is passing through the inactive region the other is in the position of maximum action. There is no reason why these two loops should not have each a separate 2-part commutator like that of Fig. 24; and one pair of brushes might press on both commutators. It is, however,

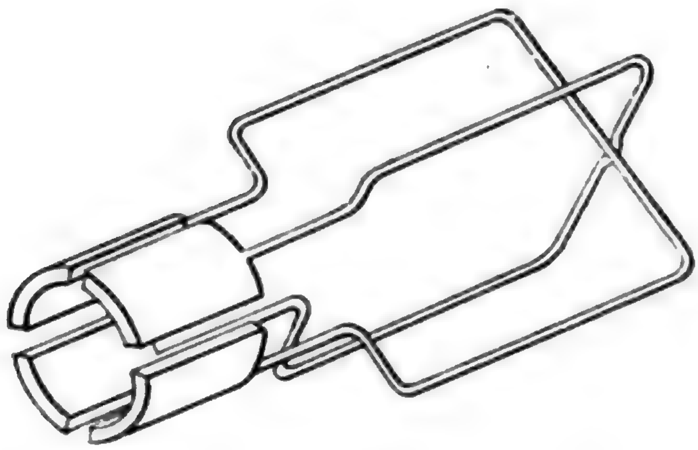


Fig. 299.
Simple Open-coil Armature.

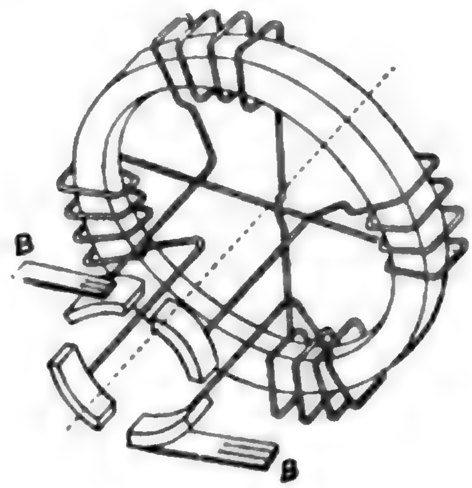


Fig. 300.—Four-part Open-coil Ring Armature.

obviously more convenient to unite these two commutators into a single one of four parts, as in Fig. 299; and then it will at once be seen that as this rotates between its pair of brushes one loop only will be in action at once, the other loop being cut out of circuit for the time being. It would clearly be possible to arrange any number of loops or coils in this way so that only that loop or coil which was passing through the position of maximum action should be feeding the brushes, all the rest being meantime open-circuited. A ring armature wound in sections might of course be similarly arranged, so that the pairs of sections have each a separate commutator; and Fig. 300 (which should be compared with

Fig. 31, p. 38) shows such a ring, but with the two commutators cut down and formed into a 4-part collector.

It will be noticed that each coil is joined at the back to the one diametrically opposite to it, and that the front ends of the coils pass to the commutator. As a matter of fact, it would make no difference in either of these armatures were the wires which cross at the back all united where they meet.

It will be seen that the position of the brushes with respect to the position of maximum action will not be the same as in the case of a closed-coil winding. In a closed-coil winding the diameter of commutation is near the coils of minimum action. With open-coil armatures the current is led directly from the coils of maximum activity.

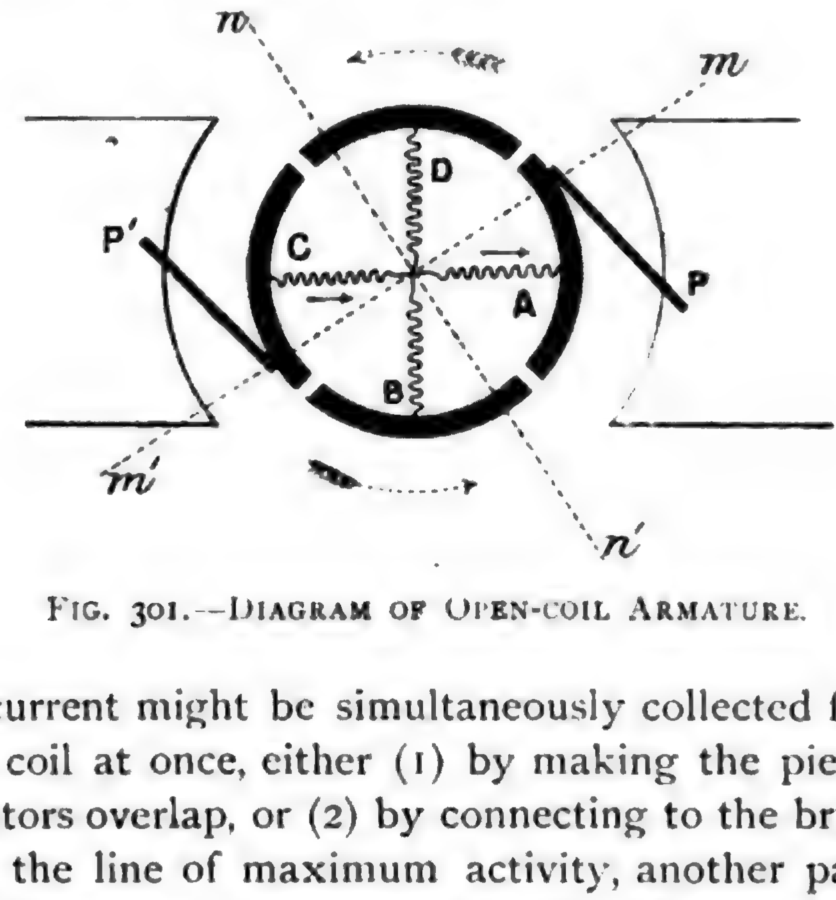


FIG. 301.—DIAGRAM OF OPEN-COIL ARMATURE.

The current might be simultaneously collected from more than one coil at once, either (1) by making the pieces of the commutators overlap, or (2) by connecting to the brushes that touch on the line of maximum activity, another pair having either a forward or a backward lead. If we now consider Fig. 301 we shall see this a little more clearly. This figure is a diagram of such an armature, the coils or loops being here represented merely by wavy lines.

The wavy line A C may represent either a pair of coils such as there are in Fig. 300 on the ring, or may represent a single loop or group of windings round a drum. There is a pair of commutator-plates for A C, and another at right

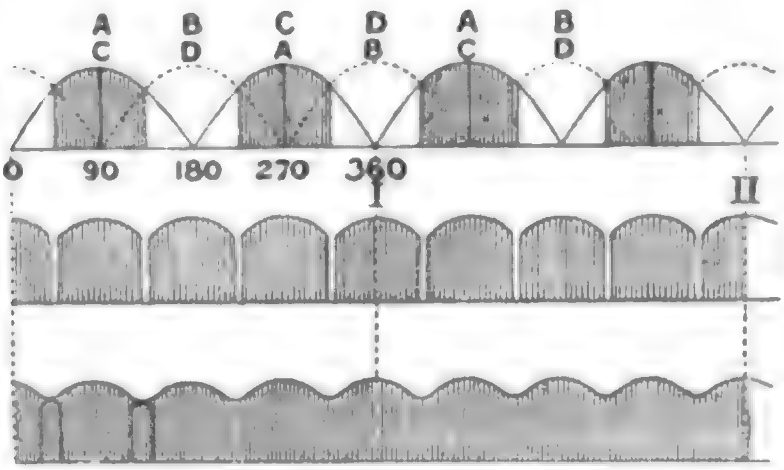
angles for B D. Coils A and C are just coming into the position of best action shown by the line $m\ m'$; they are delivering a current to the brushes P P, and this current will accordingly increase a little, and then decrease again. Meantime coils B and D are idle. If the four parts of the compound commutator each occupy just a quarter of the circumference, it is clear that when A comes into action its plane makes an angle of 45° with $m\ m'$, and that just as it leaves contact with the brush it makes again an angle of 45° on the other side, being in contact in all intermediate positions; and so with each coil as it passes the brushes. There will be a momentary break of current and a spark as the two successive segments pass under the brush, unless the brush touches both at once. Remembering that Fig. 29, p. 38, represents the alternating electromotive-force from a single loop or pair of coils, and that Fig. 30, p. 38, represents the same electromotive-force rectified by the use of a simple 2-part commutator, we shall be able to represent the effect of our new arrangement by some such diagram as Fig. 302. The angles marked below are reckoned from the neutral line $n\ n'$. When coil A has gone round 90° from this position, it is in the position of maximum induction: but because segment A of the commutator is itself 90° in breadth, the current will be collected from 45° to 135°. The shaded portions of the curve show the discontinuous effect due to the coils A and C coming into circuit during two quarters of the rotation. The coils B and D come in in the intervals as indicated by the dotted lines. The induced currents will therefore present an approximate continuity depending on the arrangements of the commutator and the brushes. Fig. 303 represents the effect if there were gaps between the segments and the commutator; and it will be noticed that the electromotive-forces, though all of the same sign, are discontinuous. If the brushes thus left contact with one segment of the commutator before the next come into contact there would inevitably be a considerable amount of sparking. Fig. 304 shows the result of making contact with one set before the other set is cut out; the induced electro-

motive-force being now continuous, but with undulating fluctuations of strength. During the time when both sets of coils are in contact with the brushes, they are, of course, in parallel with one another. During this stage of the action the resistance of the armature is half as great as when one of the coils is cut out; but it is necessary to cut out the idle coil, otherwise some of the current from the active coil would flow back uselessly through the idle coil that was in parallel with it. During the time when the two sets of coils are in parallel they are not equally active. The induced electromotive-force is increasing in one and diminishing in the other; there is but a moment when they are equally active —when they make equal angles with *m m'*. At all other

FIG. 302.

FIG. 303.

FIG. 304.



CURVES ILLUSTRATING THE PRODUCTION OF CURRENTS BY USING AN OPEN-COIL 4-PART ARMATURE.

moments the higher electromotive-force of the more active coil tends to send a back-current through the less active coil. This is to a certain extent opposed by the self-induction of the less active coil, and if contact is broken just at the moment when the higher electromotive-force has reduced the current in the less active coil to zero, the commutation will be sparkless.

From what has now been said, it will be clear that open-coil armatures may be constructed either as rings, drums, or disks. They may be arranged to run either in a simple or in a multiple magnetic field. The principal dynamos constructed upon this plan are the Brush machine and the Thomson-Houston machine; but there are a few others which also come within the category of open-coil dynamos.

Brush's Dynamo.—One of the best known of these machines is the Brush dynamo (Fig. 306). The magnet heads are insulated with sheets of the so-called vulcanised fibre, thoroughly varnished. The cores are, however, first surrounded with a thin sheet of copper, soldered together at the edges so as to form a continuous tube or envelope. The object of this copper coating is to deaden sudden variations of magnetism of the iron cores. Over the copper envelope are wound four or five thicknesses of very heavy paper saturated with shellac varnish to insulate the wire from the iron. In some of the Brush dynamos there is a double winding, a shunt or "teazer" circuit being added to maintain the magnetism

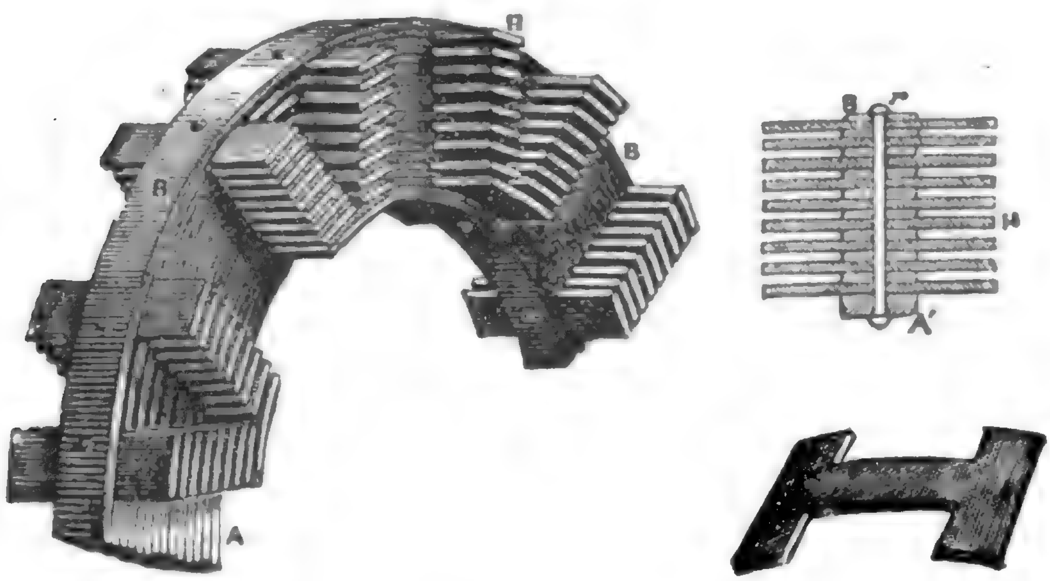


FIG. 305.—CORE OF BRUSH RING.

of the field-magnets when the main circuit is opened. An automatic regulator, consisting of a carbon rheostat connected as a shunt to the magnet winding and operated by a solenoid in the main circuit, is applied to keep the current constant (see p. 224, and Chapter XXIX.).

The armature has, like the Pacinotti ring, projecting teeth between the coils, but, unlike that early form of armature, the successive sections are not connected in a closed circuit.

The ring is built up of a thin iron ribbon 1·5 millimetres thick. Fig. 305 shows its construction, though in reality a larger number of pieces of thinner iron than is shown are used. The ribbon is wound upon a circular foundation ring

A′, projecting cross-pieces of the same thickness (marked H) being inserted at intervals to separate the convolutions, admit of ventilation, and form suitable projections between which to wind the coils. It is secured by well-insulated radial bolts. All iron parts which are to adjoin the wire of the "bobbins" are covered first with a layer of strong heavy canvas saturated with shellac varnish, and in the case of the armatures of the larger machines there are additional layers of tough paper saturated with shellac varnish. A sheet of strong cotton cloth inserted occasionally separates contiguous layers of wire from each other both in the armature bobbins and in the coils of the field-magnets. All the bobbins are wound by hand, in the same direction, and the inner ends of diametrically opposite bobbins are soldered together, and carefully insulated from all other wires and adjacent metal. The free outer ends of each pair of bobbins are separately carried through a boring in the shaft, and connected to diametrically opposite segments of the commutator.

For each pair of coils there is a separate commutator. In the No. 8 L size of machine, which is depicted in Fig. 306, there are 12 coils on the armature, six commutators grouped in three pairs, and three sets of brushes. This size is commonly known as a "60-light" machine. Its electromotive-force at a speed of 800 revolutions per minute is 3000 volts.

In considering the method in which the coils are joined up to the commutator, we will take the case of an 8-coil armature with the commutators grouped in two pairs; it will then be easy to extend the method to the case of a twelve-coil machine.

Continuity is obtained in the currents by making the two parts of the commutator of each pair of coils overlap those of the commutator belonging to the pair of coils that is at right angles, one pair of brushes resting on both commutators. Fig. 307 is a diagram illustrating this device. Each pair of segments overlaps the other to the extent of 45°. Each of the two pairs of coils is thus cut out twice during a revolution; it is twice in circuit alone, as when the brushes are at A A′, and four times in circuit along with the pair that are at

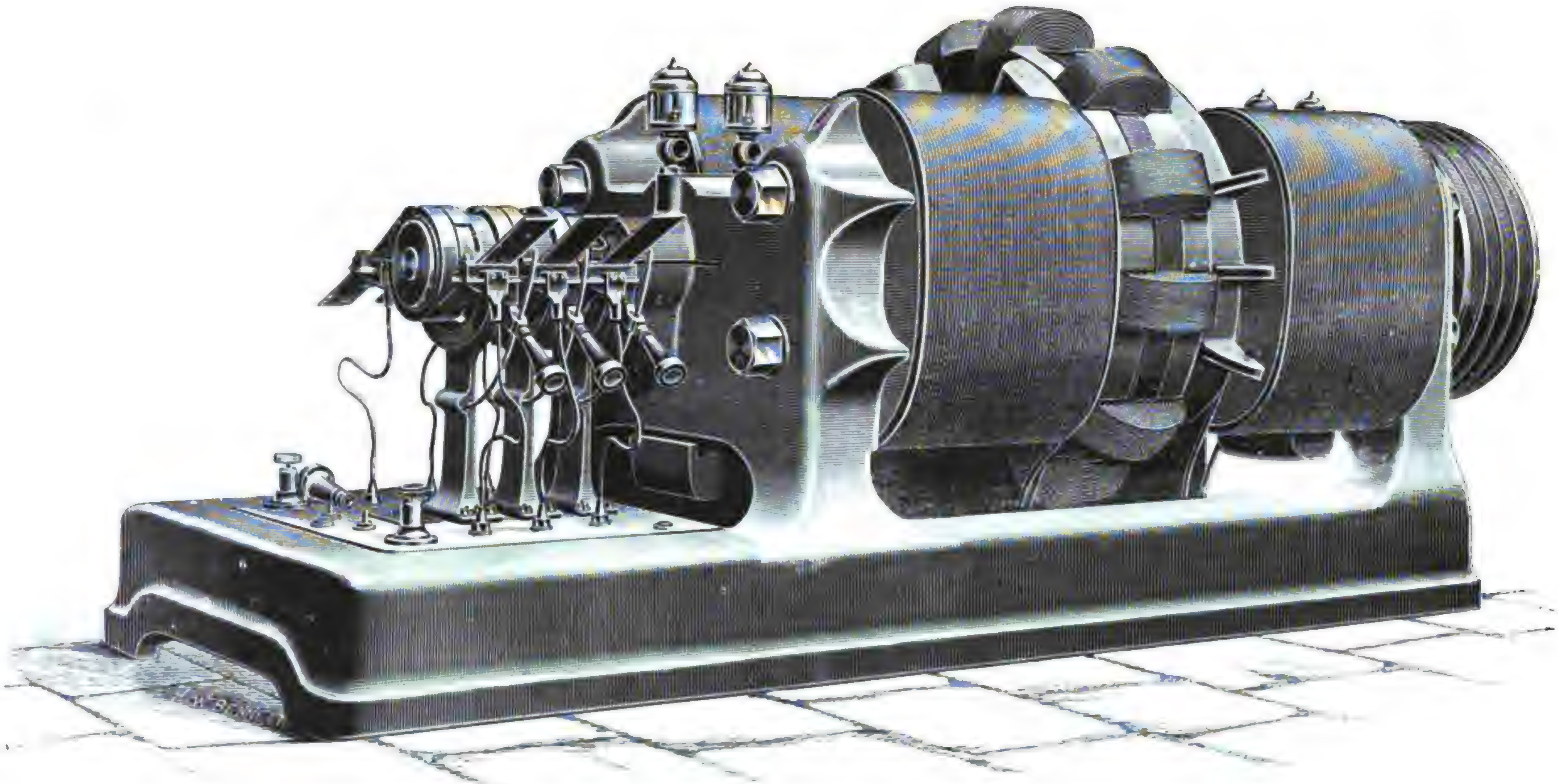


FIG. 306.—BRUSH ARC-LIGHT DYNAMO.

right angles, when the brushes are at B B′. Fig. 308 shows in perspective the commutator of an 8-coil Brush armature. There are really four commutators here, corresponding to the four pairs of coils, grouped in pairs; one pair of commutators being set one-eighth of a rotation (45°) in advance of the other. It will be seen from this figure that while the brushes A A′ (shown in dotted lines) are receiving current from *one pair* of coils only, the brushes B B′ are at the same instant receiving the current from *two pairs* of coils which are joined in parallel with one another in consequence of both of their commutators touching the same pair of brushes. The arrangement may be still further studied by the aid of Fig. 309, which also illustrates the way of connecting the brushes with the circuit. In this figure the eight coils are numbered as four pairs, and

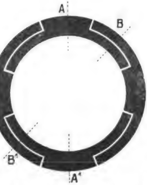


FIG. 307.—PAIR OF OVERLAPPING COMMUTATORS.

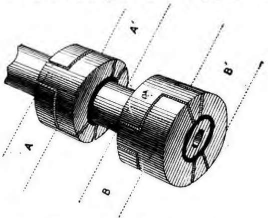


FIG. 308.—BRUSH COMMUTATOR FOR ARMATURE WOUND WITH FOUR PAIRS OF COILS.

each pair has its own commutator, to which pass the outer ends of the wire of each coil, the inner ends of the two coils being united across to each other (not shown in the diagram). In the actual machine, each pair of coils, as it passes through the position of least action (i. e. a position somewhat past the vertical dotted line midway between the poles (Fig. 309), and when the number of magnetic lines passing through it is a *maximum*, and the rate of change of these magnetic lines a *minimum*) is cut out of connexion. This is accomplished by causing the two halves of the commutator to be separated from one another by about one-eighth of the circumference at

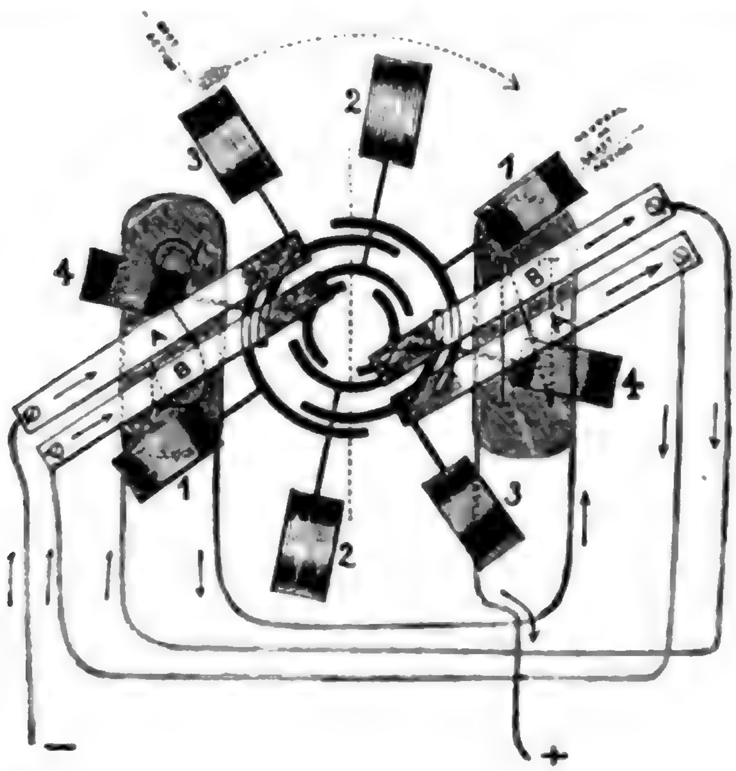


Fig. 309.—Connexions of Brush Dynamo.

each side. In the figure it will be seen that the coils marked 1, 1, are "cut out." Neither of the two halves of the commutator touches the brushes. In this position, however, the coils 3, 3, at right angles to 1, 1, are in the position of best action, and the current powerfully induced in them flows out of the brush marked A (which is, therefore, the negative brush) into that marked A'. This brush is connected across to the brush marked B, where the current re-enters the armature. Now, the coils 2, 2 have just left the position of best action, and the coils 4, 4 are beginning to approach that position. In both these pairs of coils, therefore, there will be a rather

weaker electromotive-force. The current on passing into B splits, part going through coils 2, 2, and part through 4, 4, and reuniting at the brush B′, whence the current flows round the coils of the field-magnets to excite them, and then round the external circuit, and back to the brush A.

Thus the coils in which there is a maximum electromotive-force are joined in series with coils in which the electromotive-force is weaker, though by a method different from that employed in a closed winding armature. As the armature rotates, coils 4, 4 come to the position of maximum electromotive-force, and they are then in series with coils 1, 1 and 3, 3, so that the electromotive-force of the machine varies very little with the change of the position of the coils. In some machines it is arranged that the current shall go round the field-magnets, after leaving brush A′, and before entering brush B.

The following table summarises the successive order of connexions during a half-revolution:—

First position. (Coils 1, 1 cut out.)

$$A - 3 - A'; \quad B \left\langle \begin{matrix} 4 \\ 2 \end{matrix} \right\rangle B'; \ \text{Field-magnets} - \text{External circuit} - A.$$

Second position. (Coils 2, 2 cut out.)

$$A \left\langle \begin{matrix} 1 \\ 3 \end{matrix} \right\rangle A'; \quad B - 4 - B'; \ \text{Field-magnets} - \text{External circuit} - A.$$

Third position. (Coils 3, 3 cut out.)

$$A - 1 - A'; \quad B \left\langle \begin{matrix} 2 \\ 4 \end{matrix} \right\rangle B'; \ \text{Field-magnets} - \text{External circuit} - A.$$

Fourth position. (Coils 4, 4 cut out.)

$$A \left\langle \begin{matrix} 3 \\ 1 \end{matrix} \right\rangle A'; \quad B - 2 - B'; \ \text{Field-magnets} - \text{External circuit} - A.$$

By rocking the brushes by means of the appliance provided for that purpose (see Fig. 306), a point can be found at which the sparking is reduced to a minimum (see p. 450).

From the foregoing considerations, it will be clear that the four pairs of coils in the Brush machine really constitute four separate machines, each delivering alternate currents to a

commutator, which commutes them to intermittent unidirectional currents in the brushes; and that these independent machines are ingeniously united in pairs by the device of letting one pair of brushes press against the commutators of two pairs of coils. Further, that these paired machines are then connected in series, by bringing a connexion round from brush A′ to brush B.

In the 12-coil machine (Fig. 306) there are three pairs of commutators, the segments of each pair are joined to four coils at right angles to each other, and the pairs are mounted on the shaft so that the first pair joined to coils 1, 4, 7 and 10 have a lead of 30° in advance of the second pair joined to

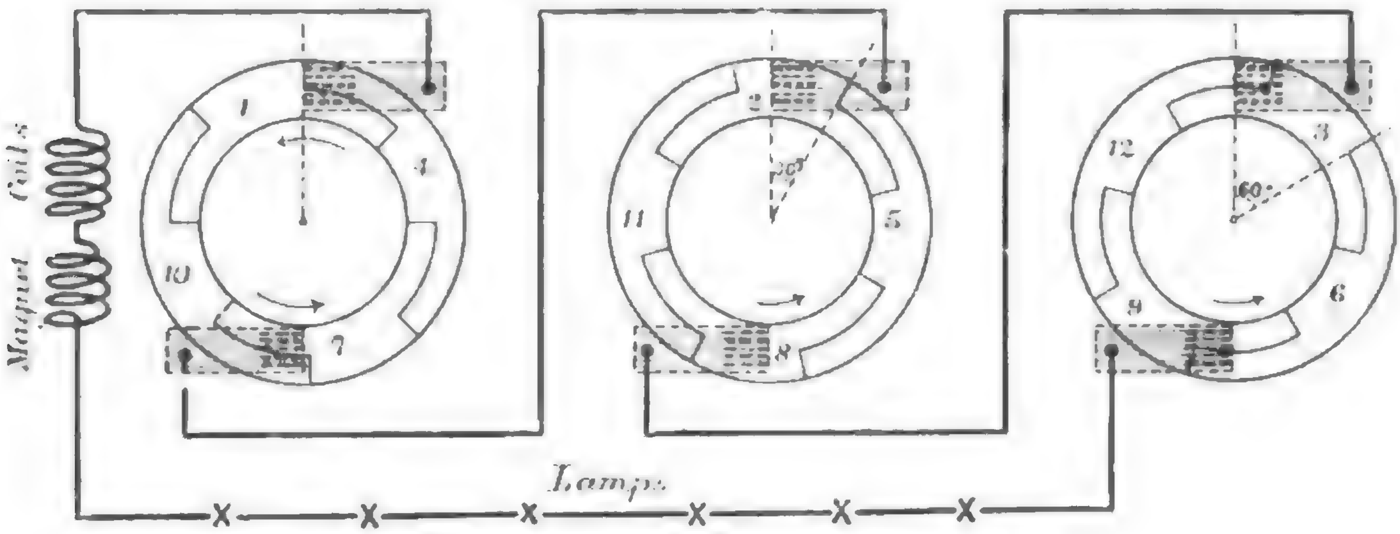


FIG. 310.—CONNEXIONS OF A 12-COIL BRUSH DYNAMO.

coils 2, 5, 8 and 11, and the third pair joined to coils 3, 6, 9 and 12 have a lag of 30° behind the second pair. The way the brushes are connected up in series is shown in Fig. 310.

Multipolar Brush machines are now made to be driven direct from the engine shaft. At the station of the Mutual Electric Light and Power Co., Chicago, there are three machines driven direct by Willans engines at 500 revolutions per minute. Each machine is capable of lighting 125 arc lamps in series. The automatic regulator regulates so closely that any number of these lamps may be thrown off and on with impunity. The armature of these machines is 39 inches in diameter and has 24 coils, that is six sets of four coils each. All the coils in any one set are in the same position relatively to the four poles, and are joined in series just as two coils are

joined in series in a 2-pole machine. The connexions to the commutators are on exactly the same principle as in the case of the 12-coil armature considered above, with this modification, that a difference of position of 45° on the armature corresponds to a difference of 90° in the 2-pole machine. Each of the three portions of the commutator, therefore, consists of eight sections, instead of four sections; the sections that are diametrically opposite being interconnected.

Some elaborate tests on Brush dynamos, with two different patterns of armature, were made[1] in 1889 by Mr. Murray of Melbourne. These showed commercial efficiencies of about 69·8 per cent. in machines with core-plates 0·05 inch thick and of about 78 per cent. in those with core-plates 0·022 inch thick. The values of B attained were about 4800 in field-magnet cores and 27,000 in the armature cores. The fluctuations of the current were about 1·5 per cent.

For further tests see Thurston in *Journal of Franklin Institute*, Sept. 1886. Consult also a small volume, "Electrical Engineers' and Students' Chart and Handbook of the Brush Arc Light System," by H. C. Reagan, jun. (New York, 1895).

Thomson-Houston Dynamo.—This machine, which is equally remarkable, was designed by Professors Elihu Thomson of Lynn and Edwin J. Houston of Philadelphia. It is unique in having a spherical armature with a 3-part commutator revolving between the cup-shaped poles of an introverted field-magnet. As will be seen from Fig. 311, the field-magnet core consists of two flanged iron tubes furnished at their inner ends with hollow cups cast in one with the tubes, and accurately turned to receive the armature. Upon the tubes are wound the coils C C′, and afterwards the two parts are united by means of a number of wrought-iron bars *b b*, which constitute the yoke of the magnet and at the same time protect the coils. The magnets are carried on a framework, which also supports the bearings for the armature shaft X. The original form of the armature, shown in Fig. 311, had a very remarkable winding. There were but three coils. The

[1] *Journal Inst. Electrical Engineers*, xvii. 710, Nov. 1889.

inner ends of these were united together *and not connected to any other conductor.* The three wires were then wound over

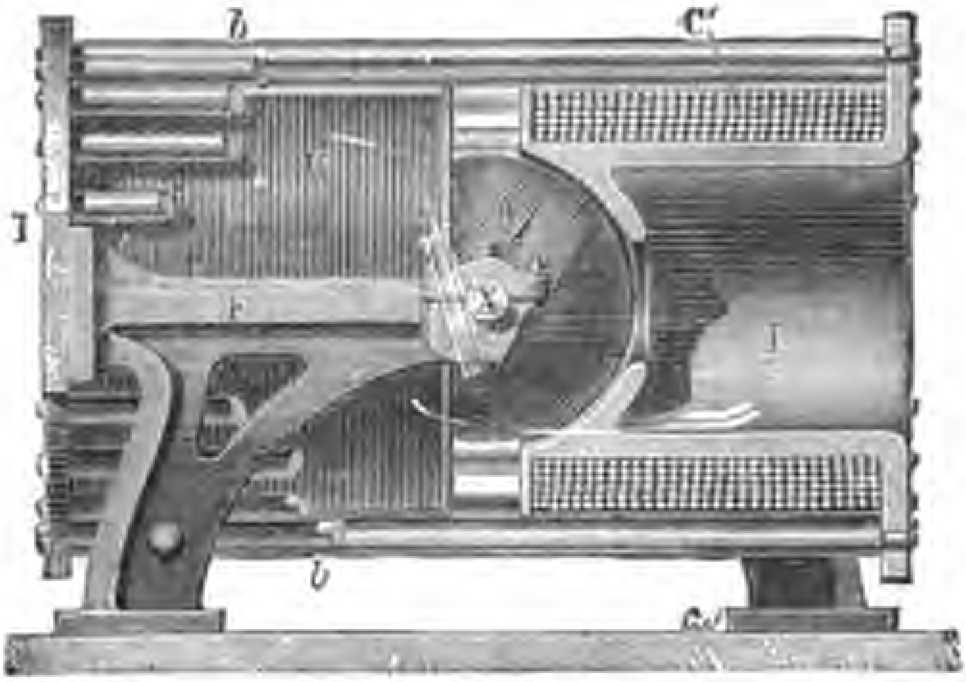


FIG. 311.—THOMSON-HOUSTON ARC-LIGHT DYNAMO.

an iron shell in three sets of windings making 120° with one another, and arranged to be at equal average distances from the core, while their overlapping made the external form

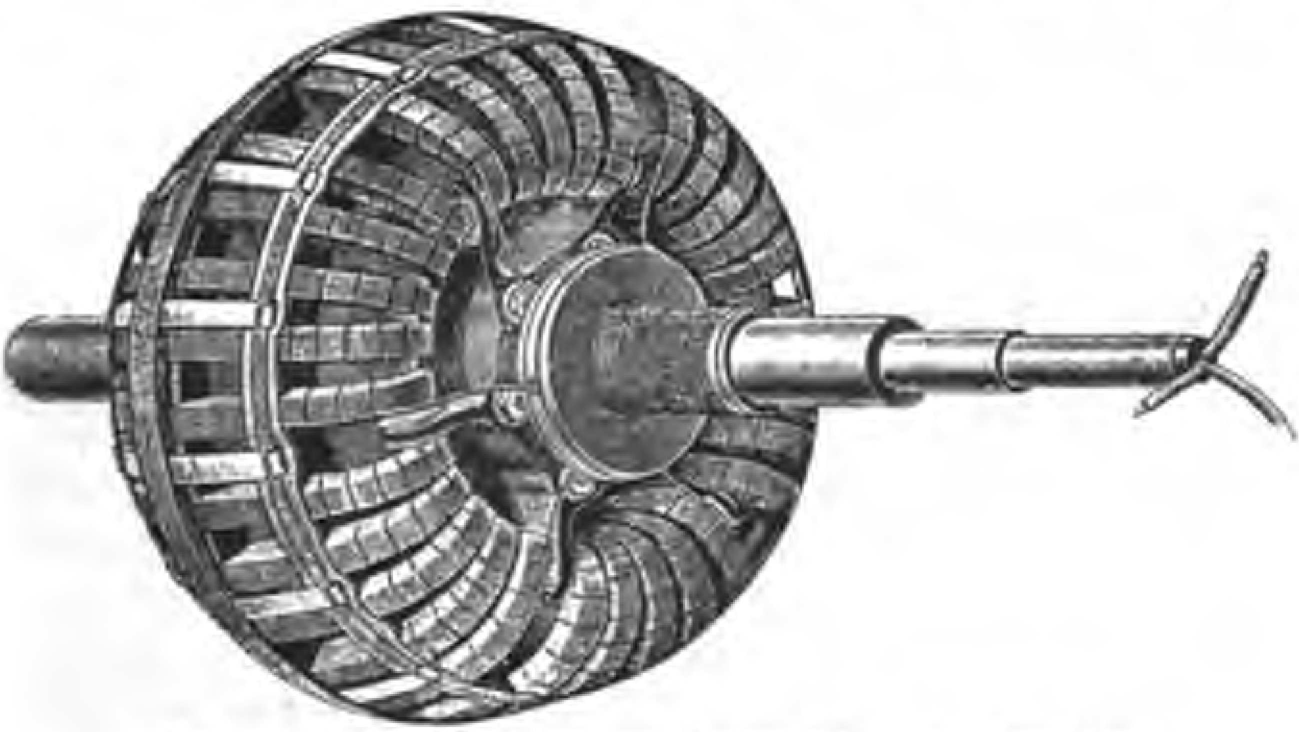


FIG. 312.—RING ARMATURE OF THOMSON-HOUSTON DYNAMO.

nearly spherical. The new ring armature, Fig. 312, has six groups of coils arranged in three pairs. The three pairs are

themselves connected star-wise, having a common junction for three of their ends, the three other ends of the wires being brought down through the hollow shaft, and joined to the three segments of the commutator. The coils are replaceable singly.

When this armature is rotated within the cavity between the cup-shaped poles alternate currents are generated in each coil in turn, and it now remains to consider how these alternate inductions are rectified and combined by the commutator. In the diagrams which follow, the rotation is represented as left-handed, as viewed from the commutator-end of the shaft, as it is in practice. Fig. 313 represents the arrangement in diagram. The three coils represented diagrammatically by

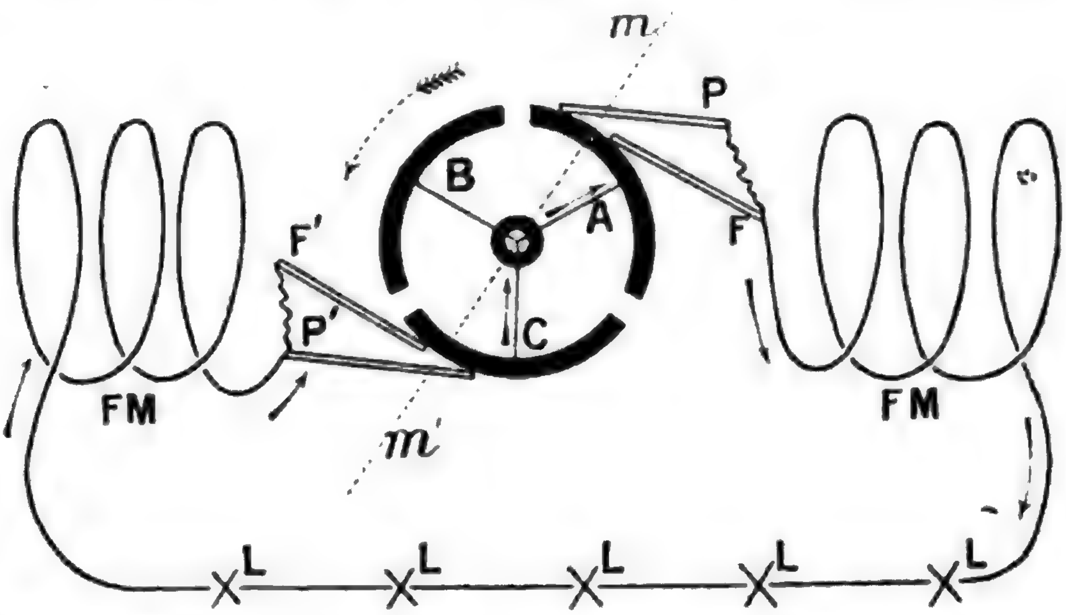


FIG. 313.—COMMUTATOR AND CIRCUIT OF THOMSON-HOUSTON DYNAMO.

the three lines A B C, are united at their inner extremities, each outer end being led to one segment of a 3-part commutator. There are two positive brushes P and F, and two negative brushes P' and F'. The current delivered to P and F first flows round one of the field-magnets, thence goes to the outer circuit of lamps, returning through the other field-magnet to P' and F'. The reader should compare this diagram with Fig. 309, and note that in that figure the neutral line divides the armature obliquely into two halves, the induced currents flowing outwardly from centre to commutator in all coils that are rising through the right-hand half of this obliquely divided circle; and inwardly from commutator to centre in all

coils descending through the left-hand half of the rotation. Accordingly, in Fig. 313, in which the neutral line is at right angles to $m\,m'$, there will be an outward current in A and an inward one in C; B being for the moment cut out of circuit as it passes through the neutral position. Continuity is obtained by the device mentioned on p. 448, of having the second pair of brushes F F' following the pair P P'. In this position of the armature A and C make about equal angles with the line of maximum action $m\,m'$, hence the two electromotive forces in these coils are for the moment about equal, but that in A is increasing, that in C decreasing. As these coils are now in series, their separate electromotive-forces are of course added together. A moment later A will be in the position of maximum induction; C will be rapidly approaching the neutral position and B will again begin to have electromotive-force induced in it. B and C will for the moment be in parallel with one another and in series with A. Then C comes to the neutral position and is cut out of circuit, while A and B are in series, and so forth.

If the width of the gaps between the segments of the commutator be equal to the width between the adjacent brushes, each coil will be out of circuit whenever it is more than 60° from the position of maximum action, and the time during which any two coils are in parallel will be practically nil. But if the brushes F F' follow at a considerable angle—about 60° in practice—behind the brushes P P', there will be considerable duration of the stage during which two coils are in parallel.

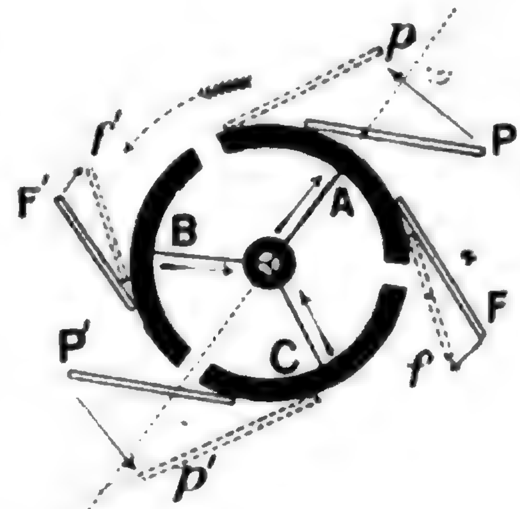


Fig. 314.—Commutating Positions.

The regulation of this machine to maintain a constant current is accomplished by an automatic shifting of the brushes. The actual method now used is termed "backward" regulation. The pair of "following" brushes F F' is shifted

backwards to ff' as shown in Fig. 314, whilst at the same time the leading brushes P P′ are shifted forward through an angle one-third as great towards pp'. If, as stated above, the brushes are 60° apart under normal conditions, there will be exactly 120° on either side between the positive brushes P F and the negative brushes P′ F′; and as 120° is the exact length of each segment of the commutator, no coil will be cut out, and parallelism will subsist between two coils through angles of 60°: that is to say, there will always be two of the three coils in parallel with one another and in series with the third coil. The six stages of change will be :—

$$\text{From external circuit} — \left\langle \begin{array}{c} F' - B \\ P' - C \end{array} \right\rangle A \left\langle \begin{array}{c} P \\ F \end{array} \right\rangle — \text{to external circuit.}$$

$$\text{,, ,, ,,} — \left\langle \begin{array}{c} F' \\ P' \end{array} \right\rangle B \left\langle \begin{array}{c} A - P \\ C - F \end{array} \right\rangle — \text{,, ,, ,,}$$

$$\text{,, ,, ,,} — \left\langle \begin{array}{c} F' - A \\ P' - B \end{array} \right\rangle C \left\langle \begin{array}{c} P \\ F \end{array} \right\rangle — \text{,, ,, ,,}$$

$$\text{,, ,, ,,} — \left\langle \begin{array}{c} F' \\ P' \end{array} \right\rangle A \left\langle \begin{array}{c} C - P \\ B - F \end{array} \right\rangle — \text{,, ,, ,,}$$

$$\text{,, ,, ,,} — \left\langle \begin{array}{c} F' - C \\ P' - A \end{array} \right\rangle B \left\langle \begin{array}{c} P \\ F \end{array} \right\rangle — \text{,, ,, ,,}$$

$$\text{,, ,, ,,} — \left\langle \begin{array}{c} F' \\ P' \end{array} \right\rangle C \left\langle \begin{array}{c} B - P \\ A - F \end{array} \right\rangle — \text{\&c.}$$

Now suppose the current to become too strong owing to reduction of number of lamps in circuit, the "following" brushes are made to recede. This will shorten the time during which any single coil in passing through the maximum position is throwing its whole electromotive-force into the circuit, and will hasten the moment when it is put in parallel with a comparatively idle coil. During such movements of regulation the whole machine is momentarily short-circuited six times during each revolution by F receding so far towards P′, and F′ receding so far towards P, as that both touch the

same segment of the commutator at one instant. The action is assisted by the slight advance of P and P′, but the main object of this advance is to lessen the sparking. If the current is too weak, then the pairs of brushes must be made to close up, thereby reducing the time during which the most active coils are in parallel with those that are less active.

Regulating Gear.—This motion of advance and retreat is accomplished by the simple link-gear not shown in any of the figures. The automatic movement is imparted by the regulating electromagnet R (Fig. 315), whose pole, of paraboloidal form, attracts its armature according to the current flowing round it, and raises the arm A. The circuits which

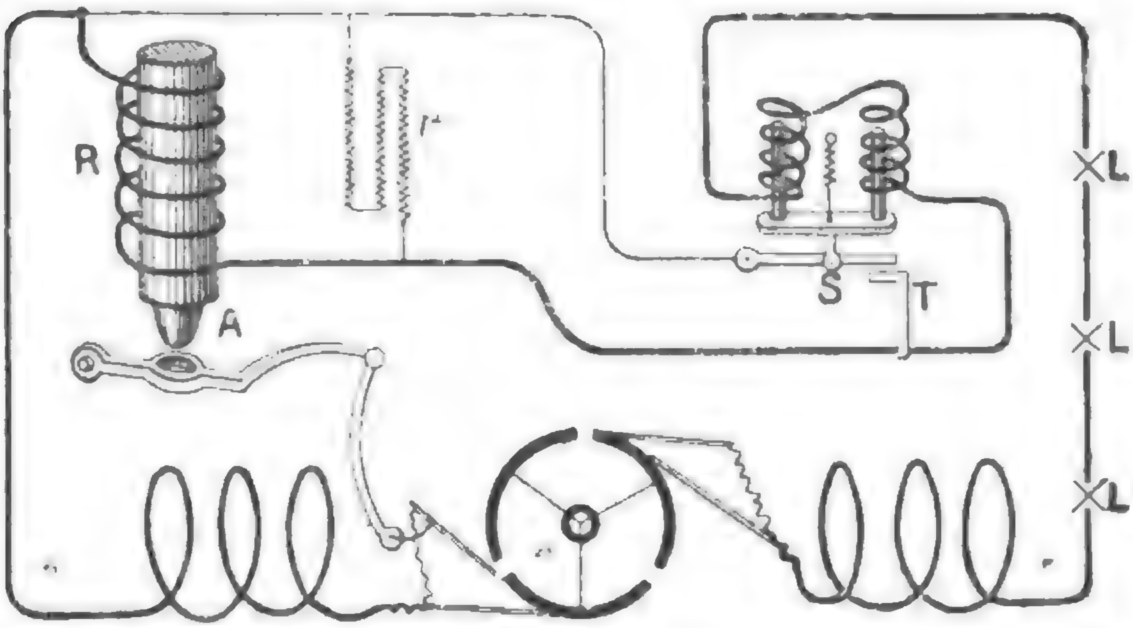


FIG. 315.—CIRCUITS OF THOMSON-HOUSTON SYSTEM.

operate this mechanism are also shown. Normally the electromagnet R is short-circuited through a bye-pass circuit, and only acts when this circuit is opened. At some convenient point of the main circuit two solenoids are introduced, their cores being supported by a spring; and the yoke of the cores operates the contact lever S. If the current becomes too strong this contact is opened, and the regulating magnet R raises the arm A. During running the lever S is continually vibrating up and down, and so altering the brushes to the requirements of the circuit. A carbon shunt of high resistance *r* is added to minimise the destructive spark at S. It might be expected that with only three parts to the commutator, the sparks occurring as the segments pass under the brushes would speedily destroy the surface. This difficulty has been met by Prof. Thomson in the boldest manner. By means of a small mechanical blower, fixed upon the shaft behind the commutator, intermittent blasts of air are blown exactly at the right moment so as virtually to blow out the spark. The three segments of the commutator are separated

by gaps; and in front of each of the leading brushes there projects a nozzle which discharges a blast, alternately, three times in each revolution.

Advantages of Open-coil Dynamos.—The two great typical open-coil dynamos—those of Brush and of Thomson-Houston—appear to have certain qualities which render them specially applicable as constant-current dynamos for series arc-lighting. A considerable proportion of all the arc-lights in the world are run by one or other of these machines. It would seem that the closed-coil dynamos, whether of the ring or of the drum type, are not so well adapted for furnishing the very high electromotive-forces needed for this work. The commutator, with its many parallel bars insulated with mica (which is the indispensable adjunct of the closed-coil armature), rapidly deteriorates when exposed to the inevitable sparking and wide alterations of lead which are inseparable from the constant-current method of working. For this method of distribution of electric energy, nothing will stand wear and tear so well as the simple air-insulated commutators described in this chapter. As a partial set-off against these advantages may be reckoned the somewhat lower plant efficiency of open-coil machines. The fluctuations in the current in well-designed machines are practically negligible. Mr. Mordey passed the current from a Brush machine through the secondary coil of a transformer, and found that no measurable difference of potential was produced at the terminals of the primary.

Some tests of a closed-coil arc dynamo have been published by Owen and Skinner in the 'Proceedings of the American Inst. Electrical Engineers' for 1893.

A special study of the curves of induction in the armature of a Thomson-Houston arc-light machine has been made[1] by Mr. Milton E. Thompson, who found the total current at full load to fluctuate between five and eight amperes, six times in each revolution; the mean current being 6·8. The fluctuations of electromotive-force in each individual coil were very remarkable; the curves being singularly irregular, falling to near zero twelve times in each revolution.

[1] *Electrical World*, xvii. 392, 1891, and *Electrical Review*, xxviii p. 773, 1891.

Other Arc-Light Machines.

Bradley's Dynamo.—Mr. C. S. Bradley has constructed a dynamo with a closed ring armature, in which the difficulty of commuting at high pressure is reduced by having four distinct commutators, the brushes of which are joined in series. A machine of somewhat similar type, designed by M. Hurmuzescu for testing purposes, is described in the next chapter.

Sperry's Dynamo.—An arc-light dynamo with a Gramme armature is that of Sperry, the distinguishing feature of which is the use of internal as well as external pole-pieces. It was illustrated in the previous edition of this book.

Wood's Dynamo.—This is also a modified Gramme machine.[1] To obviate sparking, there is an auxiliary brush placed 5 to 10 sections ahead of the collecting brush; and the voltage is varied by a device which shifts the brushes forward. The width between the auxiliary brush and that behind it is varied, being narrow where commutation has to occur in strong fields, and wide for weak fields, thus securing sparkless reversal in either case. One of the largest arc-lighting stations in the world, that at St. Louis, Missouri, is supplied with 53 of these dynamos, each capable of feeding 60 arc lamps.

Phœnix Arc Dynamo.—Mr. W. B. Esson designed arc-light dynamos[2] for Messrs. Paterson and Cooper, using Gramme ring armatures; and found no difficulty in constructing them from 800 up to 1500 volts. To promote sparkless collection in all positions of the brushes, the field in the gap space must be very constant. Hence in such machines the magnets are made with a less quantity of iron carried to a higher degree of saturation.

Statter's Dynamo.—Another example of a constant-current dynamo, with an automatic regulator to shift the brushes, is afforded by Statter's machine, in which, by a careful shaping

[1] See *Electrical World*, xii. April 23, 1887, and xiv. 54 and 260, 1889; also xvii. 4, 1891.

[2] *Journal Inst. Electrical Engineers*, xix. 161, 1890.

of the pole-faces, a disposition of the magnetic field is obtained which permits the machine to run sparklessly.

Many other makers, Mr. Crompton, Messrs. Mather and Platt, Messrs. Siemens Bros., Messrs. J. H. Holmes & Co., make good arc-light machines, with the general features of closed-coil armatures, commutators having many parts, and magnet-cores well saturated.

F. B. Crocker[1] has pointed out that it is desirable to use carbon brushes with high-voltage closed-coil dynamos, as copper wears off on the mica insulation, causing a thin film of copper which promotes sparking.

He has constructed a 5 horse-power continuous-current dynamo having 108 parts in the commutator, capable of yielding 11,000 volts.

Drooping Characteristics.—A method which, though not in itself securing constancy of current, is much followed in the construction of arc-lighting dynamos, should here be explained. Attention was drawn on p. 205 to the drooping form of the characteristics of certain series-wound machines. It is obvious that if this effect is sufficiently exaggerated, the drooping portion of the characteristic will correspond to the case of an approximately constant current. The drooping characteristic is important (see p. 223) in promoting the steady working of arc lamps in the circuit.

The causes that tend to cause the characteristic of the series dynamo to turn down after reaching a maximum height are: (1) the demagnetizing effect of the armature current when there is a positive lead at the brushes; (2) the saturating of the iron of the armature core and that of the field-magnets; (3) the leakage of magnetic lines from the field-magnet; (4) the peculiar commuting arrangements in certain machines—for example, the open-coil dynamos mentioned previously—which make their effective electromotive-force vary greatly with the position given to the brushes; (5) high internal resistance, and self-induction. As the demagnetizing effect of the armature current is nearly proportional to the current and to the angle of lead, and as the

[1] Address before Electrical Congress, Chicago, Aug. 24, 1893.

angle of lead is itself nearly proportional to the armature current, it follows that the whole demagnetizing effect is nearly proportional to the square of the armature current. In Fig. 316, let the curve E_1 represent the electromotive-force (at a given speed) when the field-magnets are separately excited, the armature circuit being left open; this includes the effect of (2) and partially (3) above. On the same diagram a curve having ordinates proportional to C_a^2, and of such a magnitude as to represent the demagnetizing action of the armature current, may be plotted. Deducting the ordinates of this curve from those of curve E_1 we get curve E_2, the drooping characteristic. The trouble with all machines of this class is the sparking at the brushes consequent on the variability of the angle of lead.

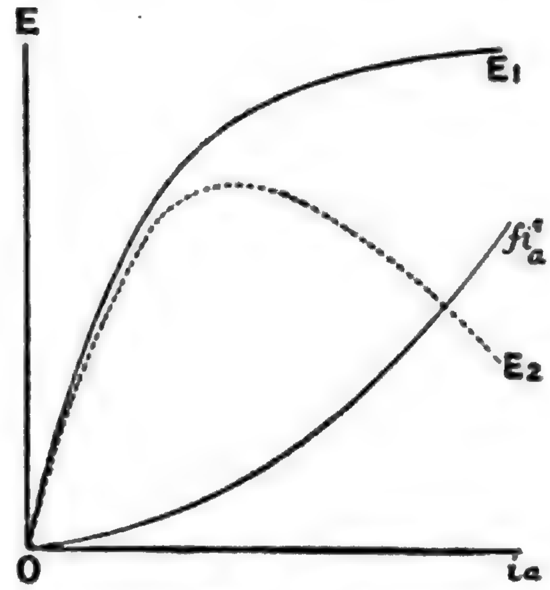


FIG. 316.

The effect of a drooping characteristic can to some extent be obtained by inserting in the external circuit a resistance of from 1 to 2 ohms. And this is preferable to having an internal resistance that would add to the heating of the armature. But such auxiliary resistance should be coiled on an iron core, since self-induction here is of value in steadying the current.

Constant-Current Regulators.—A number of devices applicable to arc-light dynamos are described in Chapter XXIX.

CHAPTER XIX.

MISCELLANEOUS DYNAMOS.

In this chapter are included Dynamos for Electrometallurgy, Homopolar Dynamos, Disk-Dynamos, and other miscellaneous forms.

Dynamos for Electroplating and Electro-metallurgy.

Special forms of continuous-current dynamo are needed for the work of electroplating, electrotyping, and the electrolytic treatment of ores and purification of metals. In general, low electromotive-forces and very large currents are requisite, for the quantity of metal deposited in the bath depends upon the quantity of amperes of current only, and not on the number of volts of electromotive-force. And though a few volts are necessary to drive the requisite current through the resistances of the circuit, the number is in every case small. To decompose water electrolytically requires less than two volts. To deposit metal in a bath in which the anode is of the same metal as the deposit requires usually a very small electromotive-force. In general, if too great an electromotive-force is employed, or if the density of current (i. e. the number of amperes per unit of area of kathode surface) is permitted, the metallic deposits will be uneven or pulveruient. All these circumstances point to the construction of dynamos having at most but four or five volts of electromotive-force, but so designed as to have an exceedingly low internal resistance. If, however, as in some processes where equal currents are wanted in a number of tanks, the tanks are

placed in series, the voltage needed will be greater in proportion to the number of cells. For example, in Castner's process for making caustic soda by electrolysing common salt solution, each tank needs 2·3 volts, so twenty tanks in series will need 46 volts.

The first application of a dynamo to the purpose of electroplating is due to Mr. J. S. Woolrich, who in 1842 patented this use of a magneto-electric machine. Wilde, however, was the first to construct machines really fitted for the purpose, when he invented the principle of using a large dynamo, the field-magnets of which were separately excited by the currents of a smaller magneto machine. His first machines, which were used for many years by Messrs. Elkington, had small exciters of the old Siemens type (Fig. 23), mounted upon electromagnets of the form shown in Fig. 100, No. 1. Both armatures were of the old shuttle-form, introduced by Siemens, and the larger one required to be kept cool by streams of water. About the year 1867 Wilde introduced a multipolar machine with a redressing commutator. Weston introduced a small machine for nickel-plating which had steel cores to the magnets but with main-circuit coils upon them, and an automatic cut-off to break the current, to prevent the magnetism from reversing by a back-current from the bath. The commutator merely rectified the currents (p. 38) without rendering them continuous. This is a bad feature; the fluctuations of the current ought to be reduced to a minimum by employing a many-part armature with a proper collector. Elmore built large dynamos, for copper refining, with eighteen electromagnets in each crown, yielding a current of 3000 amperes at a potential of seven to eight volts. Such a machine would deposit over 25 lbs. of copper per hour. The field-magnet coils were unfortunately in series with the main circuit. All electroplating dynamos should be shunt-wound or they are liable to reverse their polarity. Gramme in 1873 built special forms of very low resistance with strip-wound armatures having a commutator at each end, and giving 1500 amperes at 8 volts. Siemens and Halske also were early in the field with machines having bar armatures, which they employed

at their electrolytic works at Oker.[1] Brush also constructed large machines of low resistance for electroplating purposes. These machines had coarse wire coils connected in series, and a shunt, or so-called "teazer" coil, of finer wire to maintain the magnetism when the main circuit was opened; thus enabling the machine to do either a large or a small amount of work without fear of reversing the current. The voltage of this machine varied only from 3·3 to 4·1 volts, whilst the current varied from 300 amperes to zero.

Other dynamos have been designed for electroplating and electro-metallurgical work by nearly all the important manufacturers.

An Elwell-Parker depositing dynamo[2] gave 1500 amperes at 50 volts at 450 revolutions per minute; a 4-pole shunt-wound drum machine, with 80 stranded conductors, each of 0·2 square inch section, on the drum, and a 40-part commutator. Armature is 20 inches long and 22 inches diameter, with an unusually long commutator. Four sets of brushes, five in each set. Length of active conductor 1600 inches. At peripheral speed of 2500 feet per minute generates 1 volt for each 8 inches of conductor.

A 50 kilowatt dynamo, by Paterson and Cooper,[3] for producing bleaching liquor electrolytically, gives 1200 amperes at 42 volts.

Another 50 kilowatt dynamo, designed by Hopkinson[4] for copper refining, gives 1000 amperes at 50 volts, at 400 revolutions per minute; resistance of armature 0·0016 ohm; commercial efficiency 93 per cent.; total weight $5\frac{1}{4}$ tons.

A plating dynamo by Stafford and Eaves[5] has solid and simple magnetic circuit with one exciting coil and a ring armature with only eighteen sections, giving 150 amperes at 6 volts at 640 revolutions per minute.

In dynamos for such purposes the requirement of large current and very low voltage introduces difficulties into the design, for the voltage cannot be obtained low enough without having either very few convolutions on the armature, or else a weak field-magnet, or else a very slow-speed machine.

[1] See *Elektrotechnische Zeitschrift*, ii. 54.

[2] *Electrician*, xxi. 183, 1888.

[3] *Ibid.*, p. 181.

[4] *Ibid.*, xvii. 62, 1886.

[5] *Ibid.*, xviii. 505, 1887.

Slow-speed machines are always costly in proportion to their output. Machines with weak magnets give trouble with sparking. Machines with few massive conductors and few parts in commutator give trouble in sparking, and are liable to heat from local eddy-currents. A stranded conductor should be used, or several *independent* windings (see pp. 272 and 406), all put in parallel by brushes of special thickness.

Sayers has proposed an ingenious device to enable currents to be taken from a machine at various voltages. The pole surfaces are subdivided by deep nicks, as in Fig. 317, thus providing several neutral points on the commutator at which brushes may be placed without sparking. Thus, for example, whilst the potential between the two main brushes may be 10 volts, an intermediate brush may be employed to divide this into $7\frac{1}{2}$ volts for nickeling and $2\frac{1}{2}$ volts for silver-plating.

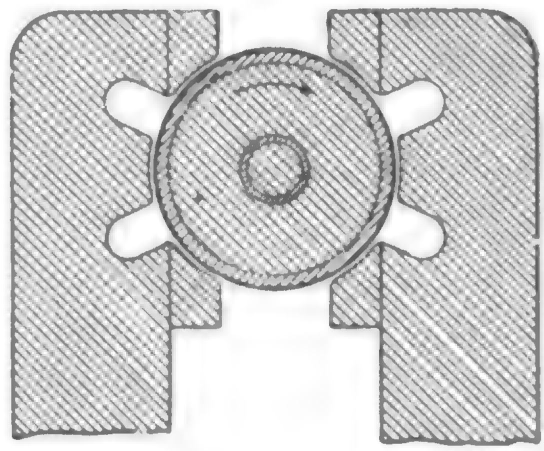


Fig. 317.—Sayers' Dynamo for Electroplating.

Messrs. Crompton & Co. have devised a method of dividing the main leads between two pairs of brushes touching adjacent bars of the commutator, and are thereby enabled to construct their plating machines with fewer parts in the armature. The divided leads from the dynamo to the plating tanks cost no more than a single undivided lead would do, but they interpose a comparatively large resistance in the path of the local current from the short-circuited section.

For the special purpose of the aluminium industry several types of machines have been developed. Messrs. Crompton & Co. built a very large 2-pole drum machine,[1] capable of affording 5000 amperes at 60 volts. Mr. C. E. L. Brown[2]

[1] *Electrician*, xxi. 590, 1888; also *La Lumière Électrique*, xxx. 207, 1888.
[2] *La Lumière Électrique*, xxx. 205, 1888; *Electrician*, xxi. 727, 1888.

designed for the Oerlikon Works some 6-pole machines for 6000 amperes at 20 volts at 180 revolutions per minute. The armatures have each two separate windings with a commutator at each end, and at each commutator 36 brushes, arranged in six sets of six each. The field-magnet is like Fig. 108, but with six poles, and cast in one piece. The armature is 38 inches in diameter and 24 inches long. The windings were at first embedded in holes in the core-disks; but as troubles arose about insulation, the core-disks were turned down, and the armature re-wound with external conductors. Although there are as many brush-sets as poles, rendering cross-connexion of the windings not absolutely necessary, yet such cross-connexions are added to ensure equalization of the currents, equipotential segments of the commutator being internally cross-connected by rings with three projecting lugs. Mr. Brown has also made some 8-pole machines for an output of 14,000 amperes at 30 volts. The 8-pole and 24-pole generators of the Oerlikon Company are described on p. 412 above.

Some statistics relating to electro-metallurgy will be found in Appendix B.

Dynamos for Accumulator-charging.

In central-station work where batteries of accumulators are used, the usual practice is to employ shunt dynamos capable of giving 25 or 30 per cent. higher electromotive-force than that at which the battery is to discharge; and their circuits are usually arranged so that the mains can be supplied, according to demand, either from the dynamos and accumulators together in parallel at the time of maximum load or from either separately.

Whenever dynamos are wanted for the sole purpose of charging accumulators, it is better to design them specially so that their magnets are not too highly saturated under working conditions. For then, during charging, when the counter electromotive-force of the cells gradually rises, the

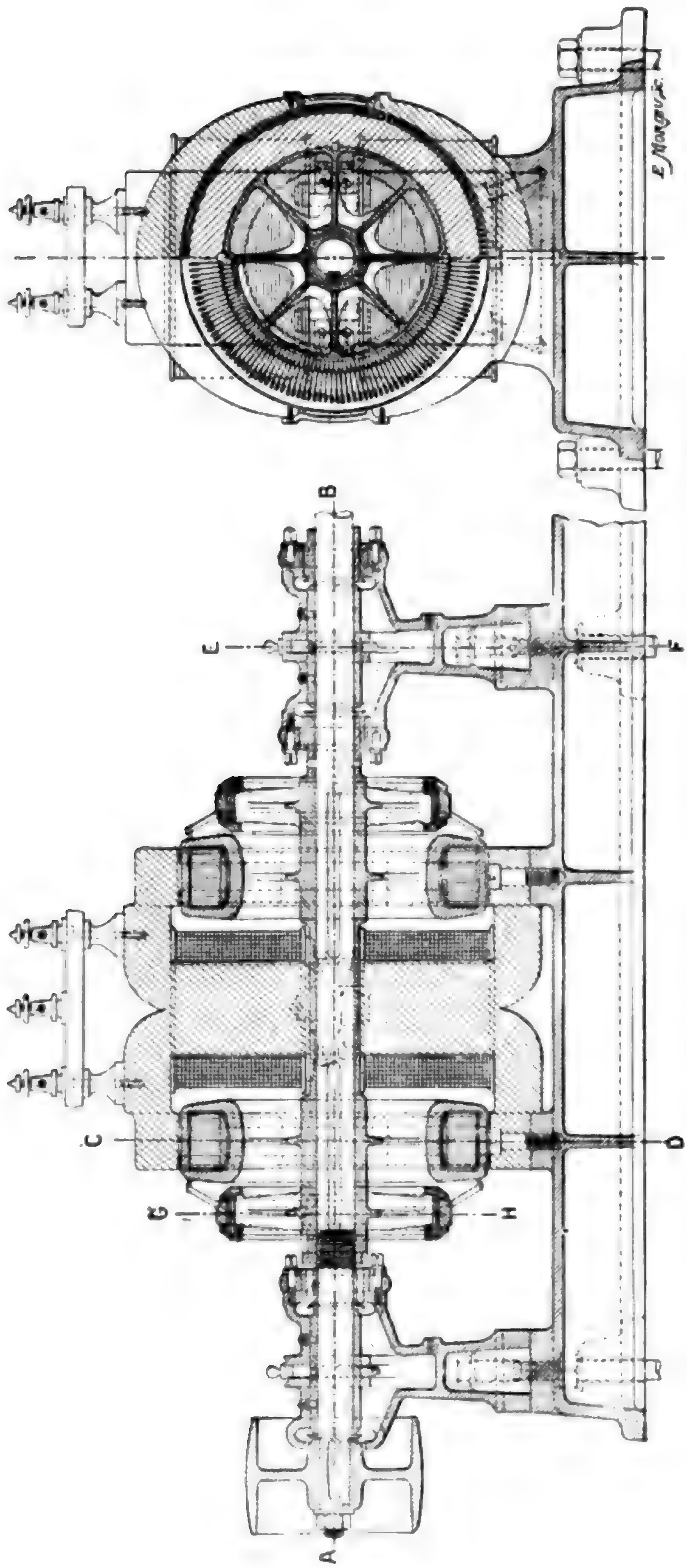
voltage of the dynamo also rises automatically, instead of remaining nearly constant as it would do if the magnetism were incapable of further rise. The result is that the charging current remains more nearly constant without intervention of an attendant.

Extra-High Pressure Dynamos.

For transmission of power to long distances by continuous currents, and for laboratory purposes, dynamos are occasionally required giving extra-high pressure. Crocker[1] has constructed a machine yielding 0·3 of an ampere at 11,000 volts, the commutator consisting of 108 parts. He recommends carbon brushes for such machines, in order to minimize the sparking. Under the direction of M. Hurmuzescu, a continuous current dynamo[2] of exceptionally high voltage has been built for the physical laboratory of La Sorbonne, by La Société Cail, to whose chief, M. Helmer, the details of the design are due. The normal output of the machine is 2 amperes at a pressure of 3000 volts, but it has yielded a pressure of 4000 volts with ease. A longitudinal section of half of the machine is shown in Fig. 318, there being altogether four armatures on the same shaft. Fig. 319 gives two different cross sections. The shape of the field-magnets being sufficiently indicated in the drawings, needs no description. The special advantage of this type of field-magnet is, that a perfectly symmetrical field is obtained without the additional cost of copper that is incident to a double magnetic circuit. There are four armatures of the ring type mounted on the same shaft, each giving a pressure of 750 volts at a speed of 1500 revolutions per minute. The winding consists of 160 sections of 66 turns per section, so there are 10,560 wires on the periphery. Each commutator is 20 cms. in diameter, and consists of 160 segments, there being a maximum of 10 volts between any two segments. The resistance of armature is 128 ohms.

[1] Address before the Electrical Congress, Chicago, August 24, 1893, *Electrical World*, xxii. 201.

[2] *L'Industrie Électrique*, July 10, 1895, p. 290.



FIGS. 318 and 319.—SECTION OF A 3000-VOLT CONTINUOUS-CURRENT DYNAMO.

HOMOPOLAR ("UNIPOLAR") DYNAMOS.

In those cases where the motion is such that the conductor moves continuously past poles of one kind only, the inductive operation is said to be *homopolar;* in cases where it passes from being opposite a N-pole to being opposite a S-pole, the operation is said to be *heteropolar.* Heteropolar operations obviously generate alternate currents, unless a commutator is added. Homopolar operations give rise to a continuous induction of electromotive-force if the field is also continuous, the rotation of the conductor effecting a continuous cutting of the magnetic lines without any reversal in direction; but in such cases, sliding connexions are necessary to collect the current. Machines giving currents by continuous homopolar induction were formerly known[1] as "unipolar" machines. If the homopolar operation is arbitrarily rendered discontinuous, as in Mordey's alternator and in some of the "inductor" alternators, by dividing up the pole-face into separate projections, and the conductor is wound alternately backwards and forwards across the field, the result will be an alternating induction.

The earliest machine which has any right to be called a dynamo (Fig. 1, p. 5), namely, the rotating copper disk of Faraday, was, in fact, of the homopolar class. So were his other machines with sliding connexions; for example, the copper cylinder rotating over the pole of a magnet (Fig. 3, p. 6). Plucker[2] devised another form, with a horizontally rotating magnet, having sliding contacts at the middle and at either end. In 1862 Mr. S. A. Varley had a homopolar apparatus with an iron magnet rotating in a vertical frame having a mercurial connexion at the middle-point. About 1878 Dr. Werner Siemens[3] designed a homopolar machine in which there were two cylinders of copper, both slit longitudinally to obviate

[1] This sounds like a *lucus a non lucendo,* for the magnet has two poles. But the name is derived from the term "unipolar induction," which continental electricians, following Prof. Wilh. Weber, give to the induction of currents by the process of "continuous cutting," which we are now dealing with.

[2] *Pogg. Ann.* lxxxvii. 352, 1852.

[3] *Elektrotechnische Zeitschrift,* ii. 94, 1881.

eddy-currents, each of which rotated around one pole of a U-shaped electromagnet. A second electromagnet was placed between the rotating cylinders, with protruding pole-pieces of arching form which embraced the cylinders above and below. Each cylinder, therefore, rotated between an internal and an external pole of opposite polarity, and consequently cut the lines of force continuously by sliding upon the internal pole. The currents from this machine are very great, but of only a few volts of electromotive-force. To keep down the resistance, many collecting brushes press on the cylinders at each end. This dynamo was used at Oker for depositing copper. Much attention has been paid in recent years to machines of this type, and the author himself designed one in which two Faraday disks, coupled at their peripheries outside an internal stationary pole-piece, rotate in a symmetrically uniform field. Mr. Willoughby Smith showed that if an iron disk be used instead of a copper disk a much more powerful effect is obtained. Prof. George Forbes has constructed several machines of this class. Originally he began by employing an iron disk which rotated between two cheeks of opposite polarity, the current being drawn from its periphery. He then doubled the parts. The next stage was to unite the two disks into one common cylinder, rotating within an entirely self-contained iron-clad field-magnet. For this reason the inventor prefers to call this type of dynamo "non-polar." A rubbing contact—for which purpose Prof. Forbes at one time used carbon brushes, and at another a number of springy strips of metal foil—is maintained at the two extremities of the periphery. One of the earlier forms of machine, with a single disk 18 inches in diameter, was stated to give 3117 amperes at a potential of 5·8 volts when running at 1500 revolutions per minute. One of the later machines, in which the armature is a cylinder of iron 9 inches in diameter, 8 inches long, is designed to give a current of 10,000 amperes at 1 volt, at 1000 revolutions per minute. In designing such machines it is convenient to remember that the voltage may be expressed in the formula

$$E = v\,l\,B \div 10^8;$$

where v is the linear velocity of the moving conductor (cms. per sec.), l its length (cms.) at right angles to the direction of motion, and B the flux-density of the field. For example, a cylinder of copper, 20 cms. broad, revolving in a field of 10,000 lines per cm., at a linear speed of 4000 cms. per second, will induce 8 volts. The electromotive-force of such machines increases as the square of the linear dimensions. Other types

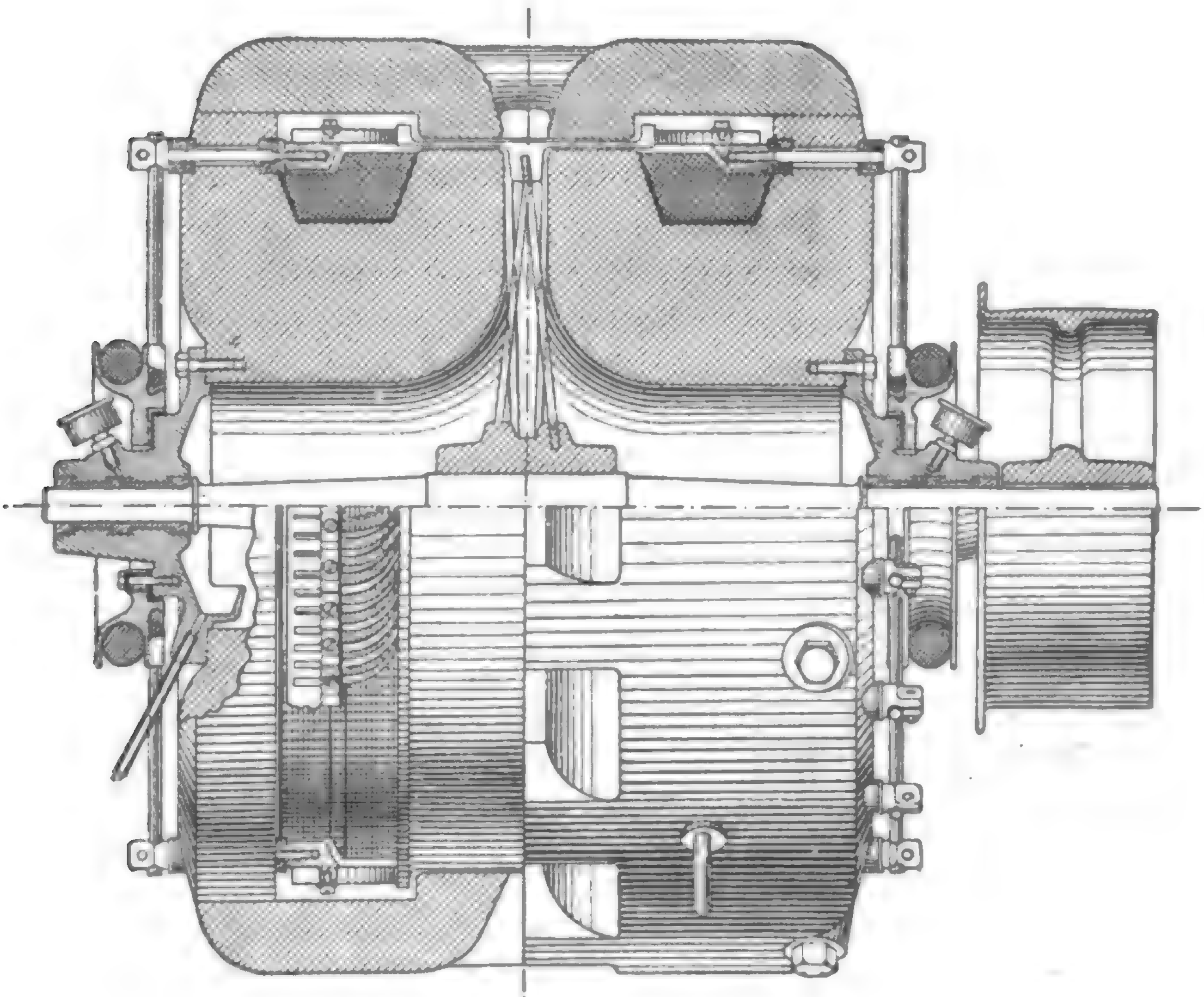


FIG. 320.—BROWN'S HOMOPOLAR DYNAMO.

have been designed by E. Ferraris, E. L. Voice, Delafield, Hummel and others, including Atkinson,[1] whose machine is self-exciting. All the important forms prior to 1885 are described and discussed by Uppenborn in the *Centralblatt für Elektrotechnik* of that year, p. 324.

The theory of the homopolar disk-dynamo has been given

[1] *La Lumière Électrique*, xxxv. 557, 1890.

by Lord Kelvin,[1] who has shown that such a machine is not self-exciting except above a certain critical speed, dependent on the resistance of the circuit.

Two difficulties seem to beset this type of machine, namely, the inherent trouble of peripheral collection of large currents, and the very considerable armature reactions which accompany these large currents, causing great fall in the voltage[2] as the current increases. The latter can only be obviated by the same expedients as hold good in all other types of dynamo, namely, to make the field-magnets relatively powerful and to counterbalance the reactions by compounding or over-compounding the machine by the use of series windings.

Mr. C. E. L. Brown has communicated to the author some results and drawings of a unipolar machine, Fig. 320, built at the Oerlikon Works, with a cylinder of copper rotating between the lips of an iron-clad electromagnet of cast iron. This machine at 1200 revolutions per minute worked at 10 volts and showed hardly any perceptible drop in voltage when 3000 amperes were taken from it. This is the first really practical homopolar machine. Since this was built a closely kindred form has been designed by M. Thury.

Much interest has been shown in recent years in the homopolar type of machine, the theory of which is still to some extent obscure. It will be sufficient to refer to the writings of Tolver Preston,[3] Hering,[4] Arnold,[5] Hoppe,[6] Weber,[7] and Lecher.[8]

Disk-Dynamos.

In the dynamos of this class the coils are carried round to different parts of a magnetic field, such that either the intensity differs in different regions, or more generally the

[1] On a uniform electric current accumulator (*Phil. Mag.*, January 1868; and *Reprint of Papers*, p. 325).

[2] See some figures given by Hummel in vol. ii. p. 19 of Kittler's *Handbuch der Elektrotechnik*.

[3] *Phil. Mag.*, February 1885, March 1885, and February 1891.

[4] *Elec. World*, xxiii. 53, 1894. [5] *Elektrotechnische Zeitschrift*, March 7, 1895.

[6] *Wied. Ann.* xxix. 544, 1886; and xxxii. 288, 1887.

[7] *Elektrotechnische Zeitschrift*, Aug. 15, 1895.

[8] *Wied. Ann.* liv. pp. 276–304, 1895.

lines of force run in opposite directions in different parts of the field. Fig. 17 (p. 29) illustrates this principle; and we shall now consider how it is carried out in practice. In the early machines of Saxton, Clarke and Stöhrer, single pairs of coils were mounted so as to pass in this fashion through parts of the field where the magnetic induction was oppositely directed. Such a machine will, therefore, give alternate currents, unless a commutator be affixed to the rotating axis.

In 1878 von Hefner Alteneck designed a disk-dynamo in which the number of coils differed by two, or some other number, from those of the field, and with the employment of a multiple-bar commutator with complicated cross-connexions. In 1881 Hopkinson and Muirhead showed a disk-dynamo with a wave-winding. In 1875 Professor Pacinotti devised[1] a form of disk-armature, which he described as a "transversal electromagnetic fly-wheel." The machine, which was exhibited at Paris in 1881, had for field-magnet two electromagnets placed with their contrary poles juxtaposed, forming, as shown in Fig. 321, a single magnetic circuit with two gaps. Through these two gaps passed a disk-armature, constructed of radial conductors arranged to cut the intense magnetic fields. The electromotive-forces induced in these conductors would on the one side be directed radially inwards, on the other radially outwards. The method devised by Pacinotti for connecting the radial conductors into a single closed coil is shown in Fig. 200, p. 279. Another type of disk-armature was invented by Lord Kelvin, consisting of a wheel with spokes like a bicycle wheel, with collecting brushes pressing against opposite ends of a diameter. Bollman[2] devised a

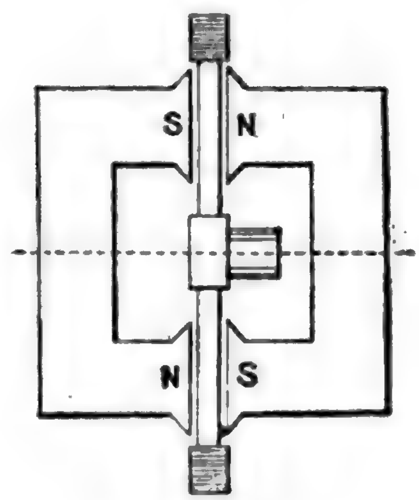


FIG. 321.—FIELD-MAGNETS OF PACINOTTI'S DISK-DYNAMO.

[1] *Nuovo Cimento* [3] X., September 1881.

[2] For detailed drawings and description, see *Centralblatt für Elektrotechnik*, ix. 7, 1887.

multipolar machine, having a complex armature built up of radial strips of copper connected in zigzag and joined to a cross-connected commutator. More recently machines of this class have been devised by Desroziers,[1] Robin,[2] Jehl and Rupp,[3] and Sayers.[4] The machines of Desroziers have been described on p. 442, and his method of winding on p. 281.

Fritsche's Disk-Dynamos.—These dynamos[5] have a disk with multipolar wave-winding with series grouping for armature. The interesting constructional feature of these machines

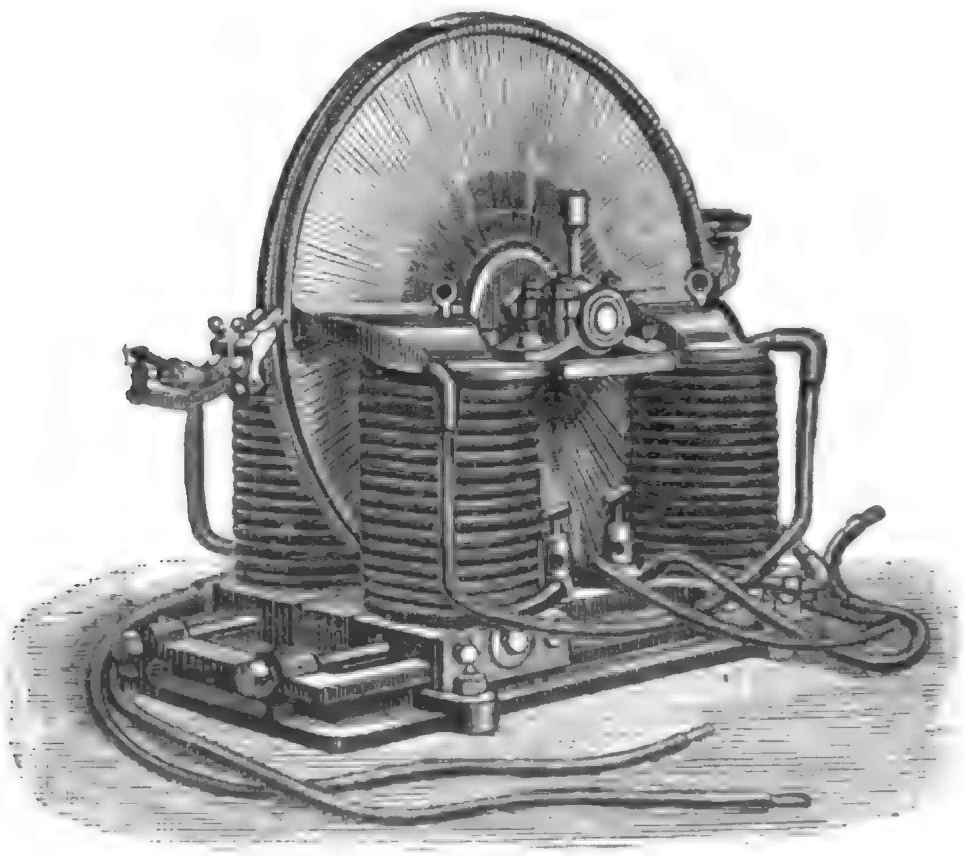


FIG. 322.—POLECHKO'S DISK-DYNAMO.

is the use of wrought-iron bars, instead of copper, as the active conductors in the disk. The commutator is fixed to the outside of the disk, with the brushes trailing against the periphery at two points.

[1] See *La Lumière Électrique*, xxiv. 293, 294 and 517, 1887; xxix. 401, 1888; and U.S. Patent No. 459, 610. [2] *Ibid.*, xxiv. 544, 1887.

[3] *Ibid.*, xxiv. 343, 1887. See also detailed illustrations and description in xxv. 368, 1887; and in *Electrician*, xix. 94, 1887.

[4] Specification of Patent, 717 of 1887.

[5] See Fritsche's book, *Die Gleichstrom-Dynamomaschine*, Berlin, 1889; also Specification of British Patent, No. 13,080 of 1887. See also *The Electrician*, xxii. 655, 1888; also *Electrical Review*, xxix. 472, 1891; and *Electrical World*, xii. 205, 1889.

Polechko's Dynamo.—This form[1] realises Lord Kelvin's suggestion for a wheel-dynamo. The wheel is 1 metre in diameter, with narrow copper spokes to rotate in a narrow gap between the pole-pieces of a pair of electromagnets, arranged to produce a very intense narrow magnetic field along two opposite radii. Fig. 322 shows its form, and the arrangement for collecting the current from the periphery, which is made up of 320 insulated pieces of copper strongly held together by an insulated steel ring at the middle of the rim. It gave, at 1500 revolutions per minute, a current of 2000 amperes at 25 volts; the entire machine weighing 1·1 tons.

[1] *Journal de la Société Physico-chimique russe*, xxii. 135, 1890.

CHAPTER XX.

CONTINUOUS-CURRENT MOTORS.

IN the first chapter, the definition was laid down that dynamo-electric machinery meant machinery for converting mechanical energy into the energy of electric currents, or *vice versâ*. Having dealt with the dynamo in its function as a generator of electric currents, we now come to its converse function, namely, that of converting the energy of electric currents into the energy of mechanical motion.

An *electric motor*, or, as it was formerly called, an *electro-magnetic engine*, is one which does mechanical work at the expense of electric energy. Any kind of dynamo, whether for continuous currents or alternating currents, can be used conversely as a motor, though, as we shall see, some more appropriately than others. Since alternate-current motors differ in their design from those intended to work with continuous currents, they will be considered later on in connection with alternate-current apparatus.

Every one knows that a magnet will attract the opposite pole of another magnet, and will pull it round. We know also that every magnet placed in a magnetic field tends to turn round and set itself along the lines of force. It is not, therefore, difficult to understand that very soon after the invention of the electromagnet, which gave us for the first time a magnet whose power was under control, a number of ingenious persons perceived that it would be possible to construct an engine in which an electromagnet, placed in a magnetic field, should be pulled round; and further, that the rotation should be kept up continuously, by cutting off or reversing the current at an appropriate moment. On this very principle was constructed the earliest electric motor of

Ritchie, so well known in many forms as a stock piece of electric apparatus, but little better in reality than a toy. Joule[1] also devised several forms of electric motor.

A still earlier rotating apparatus was Sturgeon's wheel-disk, described in 1823. This instrument, interesting, though a mere toy, as being a forerunner of Faraday's disk dynamo, is the representative of a distinctive class of machines, namely, homopolar machines (p. 475), which have a sliding contact merely, and need no commutator.

A great step in advance was made by Jacobi,[2] who, in 1838, constructed a multipolar motor.

Another class of motors may be named, wherein the moving part oscillates backwards and forwards. Professor Henry constructed, in 1831, a motor with a beam oscillating by the intermittent action of an electromagnet. In Dal Negro's motor of 1833 a steel rod geared to a crank was caused to oscillate between the poles of an electromagnet. A distinct improvement in this type of machine was introduced by Page, who employed hollow coils or bobbins as electromagnets, which by their alternate action, sucked down iron cores into the coils, and caused them to oscillate to and fro.

Page's suggestion was further developed by Bourbouze, who constructed the curious motor depicted in Fig. 323, which looks uncommonly like an old type of steam engine. We have here a beam, crank, fly-wheel, connecting-rod, and even an eccentric valve-gear and a slide-valve. But for cylinders we have four hollow electromagnets; for pistons, we have iron cores that are alternately sucked in and drawn out; and for slide-valve we have a commutator, which, by dragging a pair of platinum-tipped springs over a flat surface made of three pieces of brass separated by two insulating strips of ivory, reverses at every stroke the direction of the currents in the coils of the electromagnets. It is really a very ingenious machine, but, in point of efficiency, far behind

[1] *Annals of Electricity*, ii. 222, 1838; and iv. 203, 1839.

[2] A cut and description of this motor will be found in the former editions of this book.

all modern electric motors. It does not do to design dynamo-electric machinery on the same lines as steam engines.

Yet another now obsolete class of electric motors owed its existence to Froment, who, fixing a series of parallel iron bars upon the periphery of a drum, caused them to be attracted, one after the other, by an electromagnet or electromagnets.

Lastly, of the various historical types of motor we may enumerate a class in which the rotating portion is enclosed in an eccentric frame of iron, so that as it rotates it gradually approaches nearer. Little motors working on this principle of "oblique approach," have long been used for light experimental work.

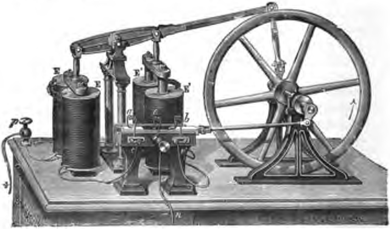


FIG. 323.—BOURBOUZE'S ELECTRIC MOTOR.

It is impossible within the limits of this work to deal with a tithe of all the various stages[1] of discovery and invention.

---

[1] An excellent account of the early forms of electric motor, both European and American, is to be found in Martin and Wetzler's *The Electric Motor and its Applications*, third edition, 1891. All readers interested in the subject should also consult the paper on *Electro-magnetism as a Motive Power*, by the late R. Hunt, in *Proc. Inst. Civil Engineers*, xvi. April 1857, together with the discussion that followed it, in which part was taken by Professor Thomson (now Lord Kelvin), Mr. (now Sir William) Grove, Professor Tyndall, Mr. Cowper, Mr. Smee and Mr. Robert Stephenson. For modern motors they should consult Kapp's *The Electric Transmission of Power*, or Snell's *Electric Motive Power*.

The work of Page, Davidson, Hjorth and others is alluded to in the Historical Notes at the beginning of this book. But the real development came after the commercial introduction of Gramme's dynamos in 1871, as engineers began to understand how two machines could be used—one as generator, the other as motor—to transmit power through a line.

All the earlier attempts to introduce electric motors came to nothing, for two reasons. Firstly, at that time there was no economical method of generating electric currents known; secondly, the great physical law of the conservation of energy was not fully recognised, and its all-important bearings upon the theory of electric machinery could not be foreseen.

While voltaic batteries were the only available sources of electric currents, economical working of electric motors was hopeless; for a voltaic battery wherein electric currents are generated by dissolving zinc in sulphuric acid is a very expensive source of power. To say nothing of the cost of the acid, the zinc—the very fuel of the battery—costs more than twenty times as much as coal, and is a far worse fuel; for whilst an ounce of zinc will evolve heat to an amount equivalent to 113,000 foot-pounds of work,[1] an ounce of coal will furnish the equivalent of 695,000 foot-pounds.

The fact, however, which seemed most discouraging, but which, if it had been rightly interpreted in accordance with the law of conservation of energy, would have been found most encouraging, was the following:—If a galvanometer was placed in the circuit with the electric motor and the battery it was found that when the motor was running the battery was unable to force through the wires so strong a current as that which flowed when the motor was standing still. The faster the motor ran, the weaker did the current become. Now there are only two causes that can stop such a current flowing in a circuit; there must be either an obstructive resistance or

[1] A convenient way of regarding the economic question from the point of view of the cost of the voltaic battery is afforded by the following calculation. Supposing the electric motor to convert all the electric energy of the battery without loss into mechanical energy, the amount of zinc used per horse-power in one hour will be almost exactly two pounds divided by the volts of electromotive-force of the cell employed in the battery.

else a counter electromotive-force. At first, the common idea was, that when the motor was spinning round, it offered a greater resistance to the passage of the electric current than when it stood still. The genius of Jacobi [1] enabled him, however, to discern that the observed diminution of current was really due to the fact that the motor, by the act of spinning round, began to work as a dynamo on its own account, and tended to set up a current in the circuit in the opposite direction to that which was driving it. The faster it rotated the greater was the counter electromotive-force (or "electromotive-force of reaction") which was developed. In fact, the theory of the conservation of energy requires [2] that such a reaction should exist. Joule,[3] by further experiment, found that the counter electric action is proportional to the velocity of rotation and to the magnetism of the magnets.

Two points are vital to the right understanding of the action of electric motors: (1) The propelling drag; (2) the counter electromotive-force. The first is that the real driving-force which propels the revolving armature is the drag which the magnetic field exerts upon the armature wires through which the current is flowing, or, in the case of deeply-toothed armatures, on the protruding teeth: the second is that the revolving armature generates a counter electromotive-force as its moving wires cut the magnetic lines.

The Propelling Drag.—In Chapter V., on the mechanical actions in armatures, the drag, which a magnetic field exerts on a conductor carrying a current, has been explained, and calculations about its magnitude given. In a generator the drag acts in a direction which opposes the rotation, and is, in fact, a counter-force or reaction against the driving force. In a motor the drag is the driving force, and produces the rotation.

The Counter Electromotive-force.—Let it be remembered

[1] *Mémoire sur l'application de l'éléctromagnétisme au mouvement des machines* par M. H. Jacobi (Potsdam, 1835).

[2] For a simple explanation of the necessity of a counter electromotive-force, see the author's *Elementary Lessons in Electricity and Magnetism* (edition of 1895, p. 443).

[3] *Annals of Electricity*, viii. 219, 1842, and *Scientific Papers*, p. 47.

that wherever in an electric circuit, current flows through some portion of the circuit in which there is an electromotive-force, the current will there either receive or give up energy according to whether the electromotive-force acts *with* the current or *against* it. This will be made clearer by Fig. 324 representing a circuit in which there are a dynamo and a motor. Each is rotating right-handedly, and therefore generates an electromotive-force tending upwards from the lower brush to the higher. In each case the upper brush is the positive one. But in the dynamo, where energy is being supplied to the circuit, the electromotive-force is in the same direction as the current; whilst in the motor where work is being done, and energy is leaving the circuit, the electromotive-force is in a direction which opposes the current. There ought to be no difficulty in understanding that this electric reaction is an essential of motor working.

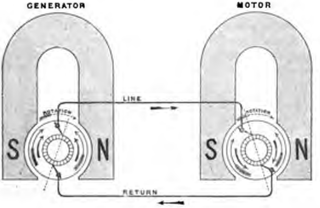


FIG. 324.

Consider the converse case, when we are employing mechanical power to generate currents by rotating a dynamo. Directly we begin to generate currents, that is to say, directly we begin to do electric *work*, it immediately requires much more power to turn the dynamo than is the case when no electric work is being done. In other words, there is an

opposing reaction to the mechanical force which we apply in order to do electric work. An opposing reaction to a mechanical force may be termed a "counter-force." When, on the other hand, we apply (by means of a voltaic battery, for example) an electromotive-force to do mechanical work, we find that here again there is an opposing reaction; and an opposing reaction to an electromotive-force is a "counter electromotive-force."

The experiment of showing the existence of this counter electromotive-force is a very easy one. All one requires is a little motor with a powerful field-magnet,[1] a few cells of battery of small internal resistance, and an amperemeter. They should be connected up in one circuit, and the deflexion of the amperemeter should be observed when the motor is held fast, and when it rotates with small and large loads. In an experiment, made on a motor with separately-excited magnets, the following figures were obtained:—

Revs. per min. ..	0	50	100	160	180	195
Amperes	20	16·2	12·2	7·8	6·1	5·1

Apparently, if the motor had been helped on to run at 261½ revolutions per minute, the current would have been reduced to zero. The current of 5·1 amperes was needed to drive the armature against its own friction at the speed of 195.

Upon the existence and magnitude of this counter electromotive-force depends, in fact, the degree to which any given motor enables us to utilize electric energy that is supplied to it in the form of an electric current. In discussing dynamos as generators, many considerations were pointed out, the observance of which would tend to improve their efficiency. It is needless to say that such considerations as the avoidance of useless resistances, unnecessary iron masses in cores, and the like, apply equally to motors. The freer a motor is from such defects, the more efficient will it be. But the efficiency

[1] One of any ordinary type—a magneto-machine or a series-wound motor will answer.

of a motor in utilising the energy of a current depends not only on its efficiency in itself, but on another consideration, namely the relation between the electromotive-force which it itself generates when rotating, and the electromotive-force or electric pressure at which the current is supplied to it. A motor which itself in running generates only a *low* electromotive-force cannot, however well designed, be an *efficient* or economical motor when supplied with currents at a *high* electromotive-force.

Elementary Theory of Electric Motive Power.

It will be shown, mathematically, that the efficiency with which a perfect motor utilizes the electric energy of the current, depends upon the ratio between the counter electromotive-force developed in the armature of the motor and the electromotive-force of the current which is supplied by the battery. No motor ever succeeded in turning into useful work the whole of the energy that is supplied, for it is impossible to construct machines devoid of resistance; and whenever resistance is offered to a current, part of the energy of the current is wasted in heating the wires that offer the resistance. Let the symbol W stand for the electric power supplied by the mains to an electric motor, and let w stand for that part which the motor takes up as useful power from the circuit.[1] These symbols may stand for the numbers of *watts* respectively supplied and utilized. All that part of the energy of the current which is not utilized by the motor, and transformed into useful work, will be wasted in useless heating of the resistances. The watts lost in heating will therefore be equal to $W - w$.

[1] The symbol w must be clearly understood to refer to the power taken up by the motor, *as measured electrically*. The whole of this power will not appear as useful mechanical effect however, for part will be lost by mechanical friction, and a minute percentage also in the wasteful production of eddy currents in the moving parts of the motor. What proportion of w appears as useful mechanical power depends on the efficiency of the motor *per se*, which we are not here considering. In all that immediately follows we shall suppose such causes of loss not to exist, or the motor will be considered as a perfect motor.

But if we want to work our motor under the conditions of greatest economy, it is clear that we must have as little heat-waste as possible; or, in symbols, w must be as nearly as possible equal to W. It will be shown mathematically that the ratio between the useful energy thus appropriated and the total energy spent, is equal to the ratio between the counter electromotive-force of the motor and the electromotive-force of supply. (As it is not wished here to complicate general considerations by introducing into the expression for the efficiency the energy wasted in heat in the field-magnet coils of the motor, we here assume that the magnetism of the field-magnets is independently excited.) The proof will be given later. Let us denote this whole electromotive-force with which the mains supply the motor (i. e. the volts measured across the terminals of the motor) by the symbol $\mathcal{E}$, and let us call the internal counter electromotive-force E. Then the rule is

$$\frac{w}{W} = \frac{E}{\mathcal{E}}.$$

But we may go one stage further. If the motor be prevented from turning, the current, as calculated by Ohm's law would be

$$C_o = \frac{\mathcal{E}}{R}.$$

If the resistances of the circuit are constant, the current C, observed when the motor is running, will be less than C_o.

$$C = \frac{\mathcal{E} - E}{R},$$

where R is the total resistance of the circuit. Hence

$$\frac{C_o - C}{C_o} = \frac{E}{\mathcal{E}} = \frac{w}{W}.$$

From which it appears that we can calculate the efficiency of which the motor is working, by observing the ratio between the fall in the strength of the current and the original strength.

Though this mathematical law of efficiency had been known for forty years it was for long ignored or misunderstood. Another law, discovered by Jacobi, not a law of efficiency at all, but a law of maximum work in a given time, was given instead. A machine does not generally do its work with the best economy when it performs the greatest work in the least possible time; and the maximum economy or efficiency of an electric motor is not when its output is at a maximum.

Jacobi's law concerning the maximum power of an electric motor supplied with currents from a source of given electromotive-force is the following:—The output of power by a motor is a maximum when the motor is geared to run at such a speed that the current is reduced to half the strength that it would have if the motor was stopped. This, of course, implies that the counter electromotive-force of the motor is equal to half the electromotive-force of supply. Now, under these circumstances, only half the energy furnished by the external source is utilised, the other half being wasted in heating the circuit. If Jacobi's law was indeed the law of efficiency, no motor, however perfect in itself, could convert more than 50 per cent. of the electric energy supplied to it into actual work.

Dr. Siemens, who first made us realize the true physical signification of the mathematical expressions which, until then, had been regarded as mere abstractions, showed, some years ago, that a dynamo can be, in practice, so used as to give out more than 50 per cent. of the energy of the current. In fact, if the motor be arranged so as to do its work at less than the maximum rate, by being geared so as to do much less work per revolution, but yet so as to run at a higher speed, it will be more efficient; that is to say, though it does less work, there will also be still less electric energy expended, and the ratio of the useful work done to the energy expended will be nearer unity than before. Or, instead of gearing it up to run fast, we may gain the same advantage by strengthening its field-magnets.

The true law of efficiency was clearly stated by Lord Kelvin in 1851, and is recognised in a paper by Joule at about the same date.

Jacobi seems very clearly to have understood that his law was a law of maximum working, but not to have understood that it was not a law of true economical efficiency. Jacobi's law is not a law of maximum efficiency, but a law of maximum output; and that is where the error creeps in. It is significant, in suggesting the cause of this remarkable conflict of ideas, that throughout the memoir which he published in 1852, Jacobi speaks of *work* as being the product of force and velocity, not of force and displacement. The same mistake is common enough among continental writers. Now the product of force and velocity is not work, but work divided by time, that is to say, "power," or "rate of working," or "activity." This may account for the widely-spread fallacy. In a paper by Achard in the *Annales des Mines* in January 1879, a clear distinction is drawn between the maximum activity and the efficiency of a motor, and he points out how as the latter increases to a maximum, the former falls to zero. In April, Sir C. W. Siemens and Lord Kelvin gave evidence on electric transmission before a Parliamentary Committee, the latter showing that it was possible to transmit 21,000 H.P. through a copper wire ½-inch in diameter, to 300 miles, provided a potential of 80,000 volts was used. Later in the same year Professors Elihu Thomson and Houston, basing their remarks upon the suggestions of Kelvin and Siemens, proposed to obtain economic results by connecting in series several dynamos at one end of a line, and several motors at the other, so as to work with small currents and high electromotive-forces. The advantage of high voltage in both dynamo and motor at the two ends of the line was never better or more clearly put than by Prof. W. E. Ayrton, in his lecture on "Electric Transmission of Power," before the British Association, in Sheffield in August 1879. These high voltages he proposed to obtain not by increasing the magnetism but by increasing the speed, and by separate excitation of both dynamo and motor. The gain in economy by allowing the motor to run at a high speed with efficiency increasing as its speed increases, was also pointed out by Dr. Werner von Siemens in his address to the Naturforscher meeting in September 1879 (see Werner von Siemens' *Wissenschaftlichen und Technischen Arbeiten*, ii. 374).

Theory of Motors.—If $\mathcal{E}$ be the electromotive-force of the mains supplying the current to the motor when the motor is at rest, and C be the current which flows at any time, the whole electric power W expended in unit time will be

expressed in watts, as the product of the whole of the applied volts multiplied by the whole of the amperes, or,

$$\text{(Total watts) } W = \mathcal{E}\, C = \mathcal{E}\frac{(\mathcal{E} - E)}{R}. \qquad [I.]$$

Now, when the motor is running, part of this electric power is being spent in doing work, and the remainder is wasting itself in heating the wires of the circuit. The useful part may be similarly written down, as the product of the armature's own volts (the counter electromotive-force) and the amperes, or

$$\text{(Useful watts) } w = E\, C = E\,\frac{(\mathcal{E} - E)}{R}. \qquad [II.]$$

All the power which is not thus utilised is wasted in heating the resistances. So we may write—

Power supplied = power utilized + power wasted in heating or,

$$W = w + \text{watts wasted in heating.}$$

But, by Joule's law, the heat-waste of the current whose strength is C running through resistance R, is expressed by the equation

$$= C^2 R \text{ (watts).}$$

Substituting this value above, we get

$$W = w + C^2 R.$$

Comparing equation [I.] with equation [II.] we get the following:—

$$\frac{w}{W} = \frac{E\,(\mathcal{E} - E)}{\mathcal{E}\,(\mathcal{E} - E)};$$

or, finally,

$$\frac{w}{W} = \frac{E}{\mathcal{E}}. \qquad [III.]$$

This is, in fact, the mathematical law of efficiency, so long misunderstood until Siemens showed its practical significance. We may appropriately call it *the law of Siemens.* Here the

ratio $\frac{w}{W}$ is the measure of the efficiency of the motor, and the equation shows that we may make this efficiency as nearly equal to unity as we please, by so adjusting either the magnetism of the field-magnets or the speed of the motor that E is very nearly equal to $\mathcal{E}$.

Now the power utilized is equal to the difference between the total power supplied and the part wasted in heat, or in symbols,

$$w = \mathcal{E}\,C - C^2\,R. \qquad \text{[IV.]}$$

In order to find[1] what value of C will give us the maximum value for w (which is the work done by the motor *in unit time*), we must take the differential coefficient and equate it to zero.

$$\frac{d\,w}{d\,C} = \mathcal{E} - 2\,C\,R = 0,$$

whence we have

$$C = \tfrac{1}{2}\frac{\mathcal{E}}{R}.$$

But, by Ohm's law, $\mathcal{E} / R$ is the value of the current when the motor stands still. So we see at once that, to get maximum work per second out of our motor, the motor must run at such

[1] The argument can be proven, though less simply, without the calculus, as follows: write equation [IV.] in the following form:

$$C^2\,R - \mathcal{E}\,C + w = 0.$$

Solving this as an ordinary quadratic equation, in which C is the unknown quantity, we have

$$C = \frac{\mathcal{E} \pm \sqrt{\mathcal{E}^2 - 4\,R\,w}}{2\,R}.$$

To find from this what value of C corresponds to the greatest value of w, it may be remembered that a negative quantity cannot have a square root, and that therefore the greatest value that w can possibly have will occur when

$$4\,R\,w = \mathcal{E}^2,$$

for then the term under the root sign will vanish. When this condition is observed it will follow that

$$C = \frac{\mathcal{E}}{2\,R},$$

or the current will be reduced to half its original value.

a speed as to bring down the current to half the value which it would have if the motor were at rest. In fact, we here prove the law of Jacobi for the maximum rate of doing work. But here, since

$$C = \frac{\mathcal{E} - E}{R} = \frac{1}{2}\frac{\mathcal{E}}{R},$$

it follows that

$$\mathcal{E} - E = \frac{1}{2}\mathcal{E},$$

or

$$\frac{E}{\mathcal{E}} = \frac{1}{2};$$

whence it follows also that

$$\frac{w}{W} = \frac{1}{2}.$$

That is to say, the efficiency is but 50 per cent. when the motor does its work at the maximum rate.[1]

[1] It may be worth while to recall a precisely parallel case that occurs in calculating the currents from a voltaic battery. Everyone is familiar with the rule for grouping a battery which consists of a given number of cells, that they will yield a maximum current through a given external resistance when so grouped that the internal resistance of the battery shall, as nearly as possible, equal the external resistance. But this rule, which is true for maximum current (and, therefore, for maximum rate of using up the zinc of one's battery), is not the case of greatest economy. For if external and internal resistance are equal, half the energy of the current will be wasted in the heat of the cells, and half only will be available in the external circuit. If we want to get the greatest economy, we should group our cells so as to have an internal resistance much less than the external. We shall not get so strong a current, it is true; and we shall use up our zincs more slowly; but a far greater proportion of the energy will be expended usefully, and a far less proportion will be wasted in heating the battery cells. The maximum economy will of course be got by making the external resistance infinitely great as compared with the internal resistance. Then all the energy of the current will be utilized in the external circuit, and none wasted in the battery. But it would take an infinitely long time to get through a finite amount of work in this extreme case. The same kind of reasoning is strictly applicable to dynamos used as generators, the resistance of the rotating part of the circuit being the counterpart of the internal resistance of the battery cells. For good economy, the resistance of the armature should be very low as compared with that of the external circuit.

Graphic Representation of Laws of Motors.

Several graphic constructions have been suggested to convey these facts to the eye; one of these enables us, in one diagram, to exhibit graphically both the law of maximum rate of working, and the law of efficiency.[1]

Let the vertical line, A B (Fig. 325), represent the electromotive-force $\mathcal{E}$ of the electric supply. On A B construct a square A B C D, of which let the diagonal B D be drawn. Now measure out from the point B, along the line B A, the counter electromotive-force E of the motor. The length of this quantity will increase as the velocity of the motor increases. Let E attain the value B F. Let us inquire what the actual current will be, and what the energy of it; also what the work done by the motor is. First complete the construction as follows: — Through F draw F G H, parallel to B C, and through G draw K G L, parallel to A B. Then the actual electromotive-force at work in the machine producing a current is $\mathcal{E} - E$, which may be represented by any of the lines A F, K G, G H, or L C.

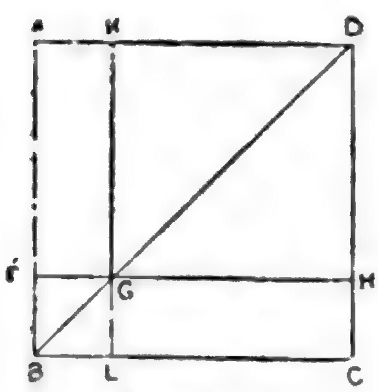


Fig. 325.

Now the electric energy expended per second is $\mathcal{E}$ C; and since $C = \dfrac{\mathcal{E} - E}{R}$, it may be written as

$$\frac{\mathcal{E}(\mathcal{E} - E)}{R};$$

and the electric energy utilized by the motor, measured in *watts*, is

$$\frac{E(\mathcal{E} - E)}{R}.$$

R being a constant, the values of the two are proportional to

$$\mathcal{E}(\mathcal{E} - E) \text{ and } E(\mathcal{E} - E).$$

[1] See paper by the author in the *Philosophical Magazine*, Feb. 1883.

Now the area of the rectangle

$$A\,F\,H\,D = \mathcal{E}\,(\mathcal{E} - E),$$

and that of the rectangle

$$G\,L\,C\,H = E\,(\mathcal{E} - E).$$

The ratio of these two areas on the diagram is the efficiency of a perfect motor, under the condition of a given constant electromotive-force in the electric supply.

Turn to Fig. 326, in which these areas are shaded. This figure represents a case where the motor is too heavily loaded, and can turn only very slowly, so that the counter electromotive-force E is very small compared with $\mathcal{E}$. Here the area which represents the energy expended, is very large; while that which represents useful work realized in the motor is very small. The efficiency is obviously very low. Two-thirds or more of the energy is being wasted in heat.

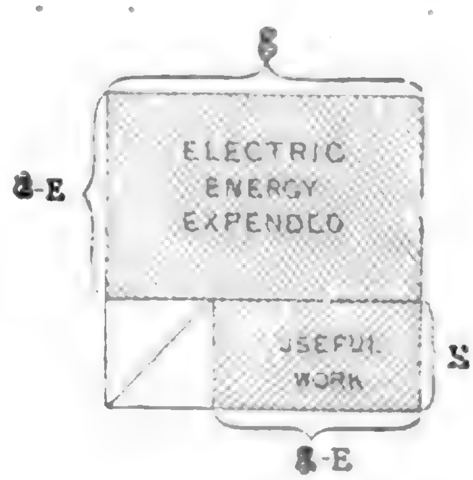


FIG. 326.

So far we have assumed that the efficiency of a motor (working with a given constant external electromotive-force) is to be measured electrically. But no motor actually converts into useful mechanical effect the whole of the electrical energy which it absorbs, since part of the energy is wasted in friction and part in wasteful electro-magnetic reactions between the stationary and moving parts of the motor. What we are expressing thus as useful work is the work actually delivered to the armature to drive it. It is a mere matter of good engineering how small a percentage of this must be discounted for friction in the bearings, eddy-currents, hysteresis and the like. If, however, we might consider the motor to be a *perfect* engine (devoid of friction, not producing wasteful eddy currents, running without sound, giving no sparks at the collecting-

brushes, &c.), then we might take the mechanical output as being precisely equal to the actual power delivered electrically to the armature. Such a "perfect" electric engine would, like the ideal "perfect" heat engine of Carnot, be perfectly reversible. In Carnot's heat engine it is supposed that the whole of the heat actually absorbed in the cycle of operations is converted into useful work; and in this case the efficiency is the ratio of the heat absorbed to the total heat expended. As is well known, this efficiency of the perfect heat engine can be expressed as a function of two absolute temperatures, namely those respectively of the heater and of the refrigerator of the engine. Carnot's engine is also ideally reversible; that is to say, capable of reconverting mechanical work into heat.

The mathematical law of efficiency of a perfect electric engine illustrated in the above construction is an equally ideal case; and the efficiency can also be expressed, when the constants of the case are given, as a function of two electromotive-forces.

Law of Maximum Activity (Jacobi). Let us next consider the area G L C H of the diagram (Fig. 326), which represents the work utilized in the motor. The value of this area will vary with the position of the point G, and will be a maximum when G is midway between B and D; for of all rectangles that can be inscribed in the triangle B C D, the square will have maximum area (Fig. 327). But if G is midway between B and D, the rectangle G L C H will be exactly half the area of the rectangle A F H D; or, the useful work is equal to half the energy expended. When this is the case, the counter electromotive-force reduces the current to half the strength it would have if the motor were at rest; which is Jacobi's law of the efficiency of a motor doing work at its greatest possible rate. Also F will be half-way between B and A, which signifies that $E = \frac{1}{2}\mathcal{E}$.

Law of Maximum Efficiency.—Again, consider these two rectangles when the point G moves indefinitely near to D (Fig. 328). We know from common geometry that the rectangle G L C H is equal to the rectangle A F G K. The

area (square) K G H D, which is the excess of A F H D over A F G K, represents therefore the electric energy which is wasted in heating the resistances of the motor. That the efficiency should be a maximum the heat-waste must be a minimum. In Fig. 325 this corner square, which stands for the heat-waste, was enormous. In Fig. 327 it was exactly half the energy. In Fig. 328 it is less than one quarter. Clearly we may make the heat-waste as small as we please, if only we will take the point F very near to A. The efficiency will be a maximum when the heat-waste is a minimum. The ratio of the areas G L C H and A F H D, which rapresents the efficiency, can therefore only become equal to unity when the square K G H D becomes indefinitely small—that is, when

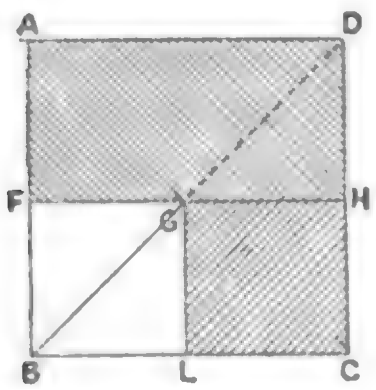


Fig. 327.—Geometric Illustration of Jacobi's Law of Maximum Activity.

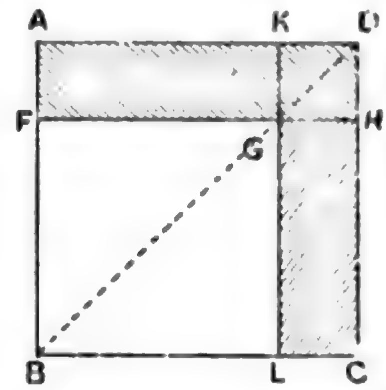


Fig. 328.—Geometric Illustration of the Law of Maximum Efficiency.

the motor runs so fast that its counter electromotive-force E differs from $\mathcal{E}$ by an indefinitely small quantity only.

It is also clear that if our diagram is to be drawn to represent any given efficiency (for example, an efficiency of 90 per cent.), then the point G must be taken so that area G L C H $= \frac{9}{10}$ area A F H D; or, G must be $\frac{9}{10}$ of the whole distance along from B towards D. This involves that E shall be equal to $\frac{9}{10}$ of $\mathcal{E}$, or that the motor shall run so fast as to reduce the current to $\frac{1}{10}$ of what it would be if the motor were standing still. Thus we verify, geometrically, the law of maximum efficiency. If there is leakage in the line, then this law will require modification,[1] for the higher the counter

[1] See Kapp's *Electric Transmission of Energy*, 4th edition, p. 185.

electromotive-force of the motor, the higher will be the potential of the line and the greater the loss by leakage.

It is now evident what we have to do to obtain any desired percentage of efficiency. Suppose current is supplied at 100 volts at the mains: then to utilize 90 per cent. we must employ as motor a dynamo which, when running at its proper speed and output, generates an electromotive-force of 90 volts.

We may now extend the graphic method to a further case.

Suppose that $\mathcal{E}$ is no longer taken as a constant, but that the work to be done by the motor per second is a constant. For this case we may write equation [II.], p. 496, as

$$E\,(\mathcal{E} - E) = w\,R.$$

This equation is graphically represented by the curve P H Q (Fig. 329), in which the values of $\mathcal{E}$ are plotted as abscissæ and those of E as ordinates. From this curve it is at once seen that there will be a certain minimum value of $\mathcal{E}$ which will suffice to give to the motor the prescribed amount of energy per second. The curve is so drawn that it passes through the corner H of all the areas equal to G L C H drawn to fit under the diagonal of the square. Of these areas, which represent equal work done by the motor, the one which has minimum value of $\mathcal{E}$ is the square which fits to the apex of the curve and corresponds to the case where $\mathcal{E} = 2$ E. This result, which was first pointed out by Prof. Carhart,[1] is the converse of Jacobi's law, and, like it, involves an efficiency of only 50 per cent. A much higher efficiency is obtained when $\mathcal{E}$ and E are both greater, as indicated by the square drawn through the point *h*.

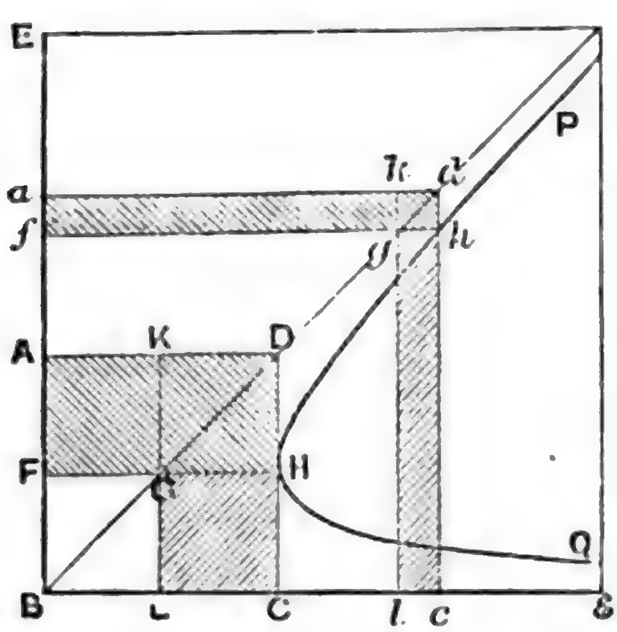


FIG. 329.

[1] *American Journal of Science*, xxxi. 95, 1886.

Speed and Torque of Motors.

Certain very important relations subsist between the condition of the electric supply and the speed and turning-moment of a motor.

In Chapter V., on Mechanical Actions and Reactions, it was set forth that the power transmitted along a shaft is the product of two factors, the speed and the torque (or turning-moment). If ω stands for the angular velocity and T for the torque,[1] then

$$\omega \, T = \text{mechanical work per second, or power.}$$

This may be expressed in watts by use of the proper coefficient.

Now if E is the electromotive-force generated by the armature, and C the current through it, the electric energy per second in the armature is the product—

$$E \, C = \text{equal electric work per second (in watts}^{2}\text{).}$$

If the whole of these four quantities, ω, T, E and C, are armature quantities, strictly, we may equate the electrical and mechanical expressions together; and the equation will be

[1] If n be the number of revolutions per *second*, then $2 \pi n = \omega$. Also if F be the transmitted pull on the belt (or rather the difference between the pull in that part of the belt which is approaching the driving pulley and the pull in that part which is receding from the driving pulley) in pounds weight, and r be the radius of the pulley, F r = the turning-moment or torque = T, then $\omega \, T = 2 \pi n r \, F$ = the number of foot-pounds per second transmitted by the belt. This may also be proved as follows: Horse-power is product of the force into the velocity. The circumference of the pulley is $2 \pi r$, and it turns n times per second, therefore the circumferential velocity is $2 \pi r n$, and this, multiplied by F, gives the work per second. If F is expressed in grammes weight, and r in centimetres, then $2 \pi r n$ F will give the power in gramme-centimetres, and must be divided by $7 \cdot 6 \times 10^6$ to bring it to horse-power, and must be multiplied by 981×10^{-7} to bring it to watts. If ω is in radians per second and T in dyne-centimetres, then the product will be in ergs per second, and can be brought to watts by dividing by 10^7.

[2] Since 1 volt = 10^8 C.G.S. units of electromotive-force, and 1 ampere = 10^{-1} C.G.S. units of current, 1 watt (or volt-ampere) will be = 10^7 C.G.S. units of work per second = 10^7 ergs per second = $10^7 \div 981$ gramme-centimetres per second.

true for either a motor or a generator. In the generator, E and C are in the same direction and T opposes ω ; or there is a counter-torque. In the motor, T and ω are in the same direction, but E opposes C ; or there is a counter electromotive-force.

In treating of the dynamo as a generator, it was assumed that the mechanical power could be supplied under one of the two standard conditions, on the one hand of *constant speed* (and torque varying with the electrical output), or else on the other of *constant torque* (and speed varying with the output). One of these two mechanical conditions being prescribed, algebraic expressions had then to be found for the two corresponding factors of the electric output, namely, the *electromotive-force* and the current, under varying conditions of resistance in the circuit. Also we investigated these conditions which would result in making one or other factor of the electric output constant. It was found convenient to study the relation between the two factors of output by the aid of the curves known as *characteristics.*

Similarly, in treating the dynamo as a motor, it will be assumed that such arrangements of electric supply can be made that the electric power can be furnished under one of the two standard conditions, on the one hand of *constant potential* (and current varying with the mechanical output of the motor), or on the other of *constant current* (and potential varying with the mechanical output). One of these two conditions being prescribed, we shall then have to find algebraic expressions for the two corresponding factors of the mechanical output, namely, the *speed* and the *torque*, under varying conditions of load on the shaft. Also, we shall investigate what are the conditions which will result in making one or other factor of the mechanical output constant : in other words, we shall ascertain what are the conditions of self-regulation to make the motor run at constant speed or with constant torque. Lastly, it will be found convenient to study the relation between speed and torque by the aid of curves, which, by analogy we may call *mechanical characteristics.*

General Expressions for Torque and Speed.

The work imparted per second to the shaft of the motor may be expressed either in electrical or mechanical measure. In the former case it is the product of the motor's electromotive-force (i.e. the counter electromotive-force opposing the electromotive-force of supply) into the current flowing in the armature; in the latter case it is the product of angular speed into torque. So we may write

$$w = E\,C_a = \omega\,T = 2\,\pi\,n\,T\,;$$

and (average) $E = n\,Z\,N$ exactly as in a dynamo that is being used as a generator (see p. 173). Hence

$$2\,\pi\,n\,T = n\,Z\,N\,C_a,$$
$$2\,\pi\,T = Z\,N\,C_a\,;$$

and finally the average value of the torque will be

$$T = C_a\,\frac{Z\,N}{2\,\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [a].$$

From this it appears that if N is constant, the torque is simply proportional to the current in the armature.

To develop this expression further, we must remember that C_a can be calculated in terms of the electromotive-force of supply $\mathcal{E}$, as measured at the terminals of the machine, and the internal resistance of the circuit through the armature part, which we call r; and then

$$C_a = \frac{\mathcal{E} - E}{r}\,;$$

whence it follows that

$$T = \frac{Z\,N}{2\,\pi}\,.\,\frac{\mathcal{E} - n\,Z\,N}{r} \quad . \quad . \quad . \quad . \quad [\beta].$$

From this it follows that when the speed becomes so great that $n\,Z\,N = \mathcal{E}$, there will be no torque. In fact, when there is no resisting force on the shaft the motor runs empty at its highest speed, namely, such as will make the counter electro-

motive-force as nearly as possible equal to the electromotive-force of supply. The maximum value of T, supposing N constant, is obviously when $n = 0$.

An expression for the speed can be obtained from the preceding:

$$2\pi T r = Z N \mathcal{E} - n Z^2 N^2;$$

$$n = \frac{\mathcal{E}}{Z N} - \frac{2\pi T r}{Z^2 N^2} \quad . \quad . \quad . \quad [\gamma].$$

In equation [α] T will be expressed in dyne-centimetres if C_a is in absolute C.G.S. units of current; if C_a is given in amperes, then the value must be divided by 10 if T is to be obtained in dyne-centimetres, or by 9810 if it is to be obtained in gramme-centimetres, or by $13 \cdot 56 \times 10^7$ if the torque is to be expressed in pound-feet (*i.e.* so many pounds weight acting at a radius of one foot).

In equation [γ], in order that n may be expressed in revolutions per second, the value of $\mathcal{E}$, if given in volts, must be multiplied by 10^8; that of r, if in ohms, by 10^9; whilst T must be reduced to dyne-centimetres. If T is given in pound-feet, its value must be multiplied by $1 \cdot 356 \times 10^7$.

Examples:—(1) In one of Brown's 4-pole machines used as motor, $Z = 368$; $C_a = 275$; giving 250 H.P. at 500 revs. per minute. Calculate the number of magnetic lines that must go through the armature. (2) A 2-pole motor is required to supply 4 H.P. in an arc-light circuit in which the current is kept at 10 amperes: How many volts must it generate? Assume $N = 2{,}000{,}000$, and that the speed is 15 revs. per second, how many armature conductors must it have?

The three equations [α], [β] and [γ] are true, not only for motors, but for generators, the $\mathcal{E}$ of the formulæ being in the latter case replaced by e. This will give negative values for T, the significance of the sign being that the torque due to the action of the magnetic field on the conductors carrying the armature current is such as to oppose the driving.

If r is very small, and N relatively very large, the second term may be neglected, and the speed will then depend on the first term only. It will be the smaller as N is greater: this being the simple converse of the corresponding fact that the more powerful the magnetic field the less need be the speed of the dynamo to give the desired output. We may also notice that if N is constant, the speed is proportional to $\mathcal{E}$: it will be constant if the condition of supply is that of

constant potential, but will be variable if $\mathcal{E}$ varies. If the motor is to do its work at a slow speed, Z should be great as well as N.

We must next inquire how n and T are affected by the fact that the value of N depends upon the construction and winding of the field-magnet of the motor, and by the conditions of supply. We shall consider the following kinds of machine:—

A. *Magneto Motor* and *Separately-excited Motor.*
B. *Series-wound Motor.*
C. *Shunt-wound Motor.*
D. *Compound-wound Motor.*

In each instance we shall have to take into account the conditions of supply, according as $\mathcal{E}$ or C is constant.

Magneto Motor and Separately-excited Motor.

It is here assumed that N is constant, in other words, that the perturbing reactions of the armature may be neglected. Under these circumstances the general formulæ already found require small modification. The only internal resistance is that of the armature r_a.

Case (i.): $\mathcal{E}$ *constant.*

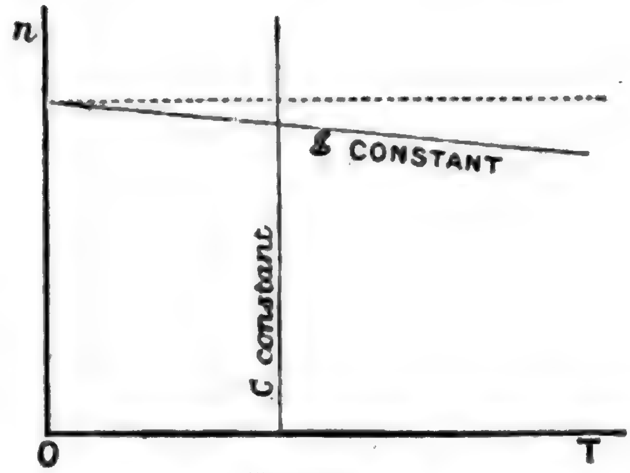


FIG. 330.
MECHANICAL CHARACTERISTICS OF MAGNETO MOTOR.

In this case formula [γ] gives the desired relation, from which the *mechanical characteristic* may be plotted out, as in Fig. 330. It is a straight line cutting the axis of n at a point representing to scale that speed at which n Z N = $\mathcal{E}$; and it slopes downwards at an angle such that the tangent of the slope is equal to

$2\pi r_a \div Z^2 N^2$, or is proportional to the internal resistance. In the case of the separately excited motor, increase in the exciting current, strengthening the field, will obviously make the sloping line more nearly horizontal, as well as lowering the speed as a whole.

If we attempt to take into account the reactions of the armature, we must remember that the effect of the armature current is to demagnetize, if there is a backward lead, and to magnetize if there is a forward lead. A backward lead, then would tend to make the sloping line, at constant $\mathcal{E}$, rise and become more level as the torque increased, because it would weaken the magnet, and so let the speed increase; whilst a forward lead would tend to make it slope still more.

Case (ii.): C *constant.*

In this case, as reference to formula [*a*] shows, the torque is constant, being independent of speed and of internal resistance. The mechanical characteristic of the machine under these conditions is a vertical straight line.

SERIES MOTOR.

The fundamental equations are as before, with the addition of the following :—

$$r = r_a + r_m;$$

but now we may with advantage introduce the approximate formula for the law of the electromagnet (derived from Frölich's) given in Chapter VI., and write, as on p. 143, where C′ is the diacritical current and $h = S\,C'$,

$$N = \bar{N} \frac{C}{C + C'}.$$

Putting this value of N into the expression [*a*], on p. 503, for the torque, and writing for brevity $\frac{Z\bar{N}}{2\pi} = Y$, we have

$$T = Y \frac{C^2}{C + C'}.$$

This relation between torque and current is given graphically in Fig. 331. For values of C that are small as compared with C′, T varies nearly as C^2; whilst for large values of C, as magnetic saturation advances, T is nearly proportional to C. The equation may also be written in the quadratic form—

$$C^2 - \frac{T}{Y} C - \frac{T}{Y} C' = 0,$$

the solution of which is

$$C = \frac{T}{2Y}\left\{1 \pm \sqrt{1 + 4\frac{Y}{T}C'}\right\}.$$

It is permissible for large values of T to neglect the second term under the root sign, since the magnetization grows nearly constant.

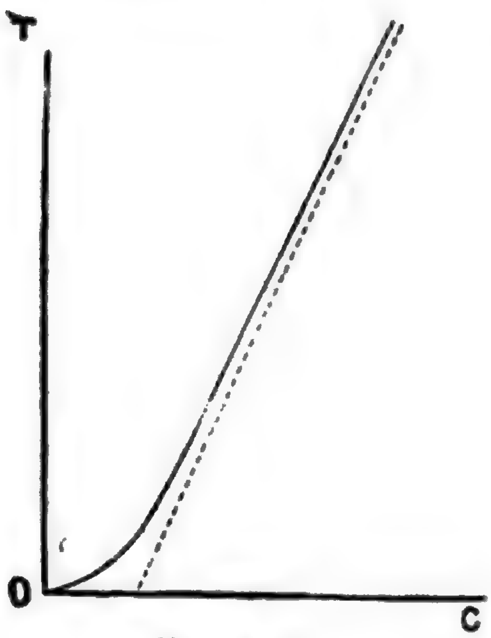


Fig. 331.

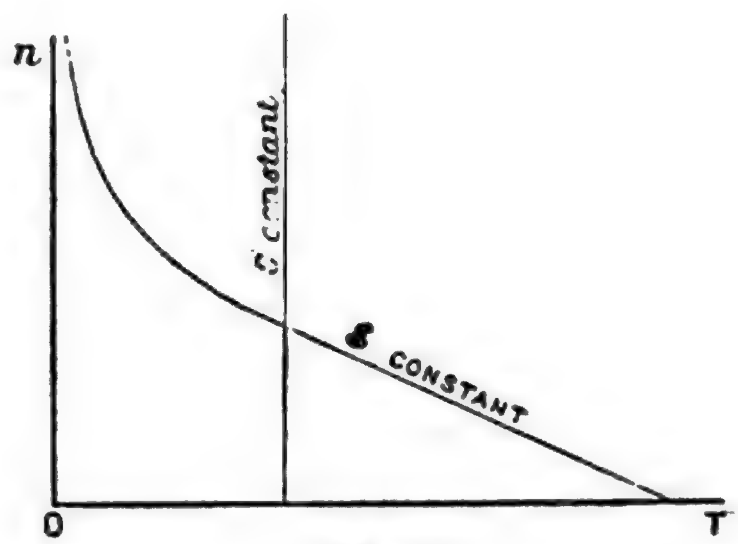


Fig. 332.
Mechanical Characteristics of Series Motor.

As an example plot the following figures taken from a test of a 30 H.P. street-car motor, where the torque is given in pound-feet, the current in amperes, and the speed in revolutions per minute:

Current	3·5	10	20	30	40	50	70	90	94
Torque	0	29	95	183	281	385	610	863	912
Speed ..	479	236	145	118	99	85	61	39	35

Now from [*a*] and [γ] above we may eliminate S N, giving

$$n = \frac{\mathcal{E}\,C}{2\,\pi\,T} - \frac{r\,C^2}{2\,\pi\,T};$$

whence,

$$n = \frac{\mathcal{E}\,C}{2\,\pi\,T} - \frac{r\,(C + C')}{2\,\pi\,Y};$$

$$n = \frac{\mathcal{E} - r\,C'}{2\,\pi\,Y} - \frac{r\,T}{4\,\pi\,Y^2}.$$

Case (i.) : $\mathcal{E}$ *constant.*

If $\mathcal{E}$ is constant, then, as the last equation shows, for large values of T the values of n are equal to a certain constant less a quantity proportional to T ; or the mechanical characteristic at this point (when the magnets are well saturated) is, for all large values of T, approximately a straight line as shown in Fig. 332.

Case (ii.) : C *constant.*

Here, clearly, saving for armature reactions, the magnetization will be constant ; hence the torque will also be constant, as in Fig. 330. With a load exceeding a certain amount, the motor will not start ; with a lesser load it will race until friction and eddy-currents make up the difference.

The properties of series-wound motors are so important that we may pause to consider them a little more fully. We know that if the current running through a series dynamo be constant, so that its magnetism is constant, the electromotive-force it develops is almost exactly proportional to its speed. It therefore follows that if E is proportional to ω, T will be proportional to C. This is abundantly verified in the case of series motors by experiments. When a Siemens series dynamo was arranged to lift a load of 56 lbs. on a hoist, it lifted this load at the rate of 212 feet per minute, developing a counter electromotive-force of 108·81 volts. The applied electromotive-force was 111 volts, and the resistance of the circuit was 0·3 ohm. The effective electromotive-force was therefore 2·19 volts and the current 7·3 amperes. When the resistance of the circuit was increased to 2·2 ohms, the speed

fell to 169 feet per minute, the counter electromotive-force to 94·94; the effective electromotive-force, $\mathcal{E} - E$, was therefore 16·06 volts, and the current 7·3 amperes as before. When 4·8 ohms were inserted, the speed fell to 141 feet per minute, and E to 76 volts; $\mathcal{E} - E$ was 35 volts, and the current 7·3 amperes as before. *With the same load, the same current,* whatever the speed.

The fact that the torque of a series motor depends only on the current is of advantage in the application of motors to propulsion of vehicles (such as tram-cars) which at starting require for a few seconds a power greatly in excess of that needed when running.[1]

In the series motor, when supplied at constant potential, E is not proportional to the speed, because the field-magnetism is not constant, but falls off as E increases, being (if unsaturated) nearly proportional to $\mathcal{E} - E$. It therefore will not run at a constant speed. Neither will it run at a constant speed if supplied with a constant current.

Use of two Series Machines in Transmission.—It is known that if two similarly-constructed series-wound machines are used—one as generator, the other as motor—the arrangement is almost perfectly self-regulating, the speed of the motor at the receiving end being almost constant if that of the dynamo at the transmitting end is constant. Every addition to the load put upon the motor, tending to check the speed, causes an increase of current to flow, and so throws proportionate additional work upon the generator, which in turn takes more power from the steam engine to keep up its speed. As we have shown above, the torque of the motor T_2 will depend, in the given machine, on the current alone, and on the current will depend the torque at the dynamo T_1. Mr. Kapp has further shown[2] how, if there is a resistance in the line, the arrangement may still be made self-regulating by choosing as generator and motor two machines so wound that comparing their characteristics for the prescribed speeds, the

[1] See remarks by E. Hopkinson, *Proc. Inst. Civil Engineers*, xci. pt. i. 6, 1887.

[2] See Kapp's *Electrical Transmission of Energy*, 4th edition, p. 199.

difference in their electromotive-forces corresponding to a given value of current shall be equal to the electromotive-force requisite to drive that particular current through the resistance in the whole circuit. See Chapter XXVIII., on Transmission of Power.

The late Sir C. W. Siemens[1] drew attention in 1880 to the singular properties of the combination of a generating dynamo and an electric motor, instancing a locomotive motor which, when descending an incline, quickens its speed and actually becomes a generator of currents, paying back the spare power into store. He also remarked how two trains driven by motors running on the same pair of electric rails, tend to regulate one another, the one on a descending portion of the road transmitting power to the other, as though "connected by means of an invisible rope."

SHUNT MOTOR.

The fundamental conditions are as follows:—

$$T = C_a \frac{Z N}{2 \pi};$$

$$C_a = C - C_s;$$

and, adopting the appropriate form for the law of magnetization,

$$N = \overline{N} \frac{\mathcal{E}}{\mathcal{E} + \mathcal{E}'};$$

$$E = \mathcal{E}\left(1 + \frac{r_a}{r_s}\right) - r_a C.$$

From the first three of these we get

$$T = \frac{Z}{2 \pi}\left(C - \frac{\mathcal{E}}{r_s}\right) \overline{N} \frac{\mathcal{E}}{\mathcal{E} + \mathcal{E}'};$$

[1] *Journal Soc. Telgr. Engineers*, ix. 301, 1880.

and, transposing and writing Y for $\mathrm{Z\,N} \div 2\pi$,

$$\mathrm{C} = \frac{\mathrm{T}}{\mathrm{Y}} \cdot \frac{\mathcal{E} + \mathcal{E}}{\mathcal{E}} + \frac{\mathcal{E}}{r_s};$$

and from the last of the four

$$n = \frac{1}{\mathrm{Z\,N}} \left\{ \mathcal{E}\left(1 + \frac{r_a}{r_s}\right) - r_a \mathrm{C} \right\}.$$

Inserting the value of C, we have

$$n = \frac{+}{2\pi \mathrm{Y}} \left\{ 1 + 2\frac{r_a}{r_s} - \frac{r_a \mathrm{T}}{\mathrm{Y}} \cdot \frac{\mathcal{E} + \mathcal{E}'}{\mathcal{E}^2} \right\}.$$

Case (i.): $\mathcal{E}$ *constant.*

The last equation shows that a shunt-motor, supplied at constant potential, will have a speed that would be constant and independent of the torque if it were not for internal resistance; and further, that the consequent falling off as the torque increases will be the less as the field-magnetism is the more powerful.

As an example, a Victoria shunt motor tested by Mr. Mordey, in which the load was varied from $91 \cdot 8 \times 10^7$ to $1357 \cdot 2 \times 10^7$ dyne-centimetres, only decreased its speed from 16·25 to 15·75 revolutions per second.

It is instructive to contrast the self-regulating power of a shunt dynamo with the self-governing power of a shunt motor. The former, when driven at a constant speed, generates electric power at a nearly constant potential; the latter, when supplied from the mains at a constant potential, would furnish mechanical power at a nearly constant speed; and in both cases the departure from absolute constancy is proportional to the internal resistance of the armature coils, and to the output electrical or mechanical, of the machine for the time being.

So far we have supposed the armature to exert no magnetic reaction. Now, as we shall see, to obtain sparkless running there must be a backward lead, and in motors a backward lead tends to demagnetize. But demagnetizing tends, as we have seen, to increase the speed; hence in the case of constant pres-

sure supply, when there is a great load, the very reaction of the great current will tend to prevent the speed from falling, making the shunt motor very nearly self-regulating. These reactions must now be considered in detail.

Case (ii.): C *constant.*

The determination of this case is more complicated, though the general considerations are simple enough. If the motor is standing still when the current is turned on, nearly all the current will go through the armature, next to none through the shunt; hence there will be little magnetism, and therefore almost no torque. Such a machine will not start itself with any load on; but if it be once started, its counter electromotive-force will cause the current in the armature to decrease, whilst that round the shunt increases. The torque will therefore then increase with the speed, but not indefinitely, for as the magnetism advances in its degree of saturation, the increase of N will no longer compensate for the decrease of C_a; and from that point onwards the torque will decrease if the speed is allowed to increase. And, hypothetically, the speed should increase until the motor's own electromotive-force exactly equals the difference of potentials due to the whole of the constant current flowing through the resistance of the shunt, under which circumstances there will be no current through the armature and zero torque. Fig. 333, which, like the preceding, is taken from Dr. Frölich's work, gives the mechanical characteristics for the two cases.

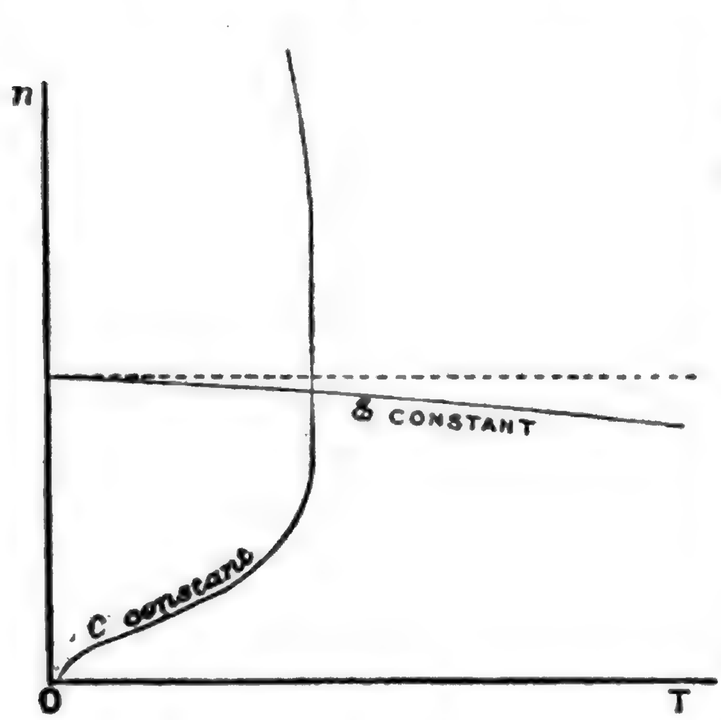


FIG. 333.—MECHANICAL CHARACTERISTICS OF SHUNT MOTOR.

Reaction between Armature and Field-Magnets in a Motor.

On pp. 70 to 80 and pp. 380 to 395, the reactions between the armature and field-magnets of a dynamo were considered in detail, but attention was confined solely to that which occurs when the dynamo is used as a generator. In that case we noted that the current in the armature tended to cross-magnetize the armature core and to distort the field in the sense of the rotation; while the forward lead of the brushes, needful for sparkless commutation of the current, tended to exercise a demagnetizing effect. The same thing is true of a motor; but with a difference. A current supplied from an external source magnetizes the armature and makes it into a powerful magnet, whose poles would lie, as in the bipolar dynamo, nearly at right angles to the line joining the pole-pieces, were it not for the fact that in this case also a lead has to be given to the brushes. Suppose, as in most of the drawings in this book, that the S-pole of the field-magnets is on the left, and the N-pole on the right. Also that the current so traverses the armature that it causes the highest point to be a S-pole and the lowest point a N-pole. This means that if the armature is wound right-handedly the current must come in through the top brush and leave by the bottom one, the top brush being connected to the + main. Compare with p. 60. Clearly, in this case, the armature will rotate right-handedly, because the S-pole at the top will be repelled from the S-pole on the left and attracted toward the N-pole on the right. It will therefore run right-handedly (in a right-hand field) when the current flows downwards from top to bottom, exactly as the armature of a generator must run in order to send a current upwards. In each case the direction of the induced electromotive-force is the same—upwards—*with* the current in the generator, *against* the current in the motor.

It follows that in a motor a *forward* lead would convert the cross magnetizing-force into one that tends to increase

that of the field-magnet, whilst a *backward* lead tends to demagnetize. Further, since with a forward lead the armature polarity strengthens that of the field-magnet, it is possible (apart from the question of sparking) for a motor to be worked without any other means being taken to magnetize the field-magnets (see p. 395): the armature will induce a pole in the field-magnet and then attract itself round towards this induced pole. This principle has been used for many years in small motors.

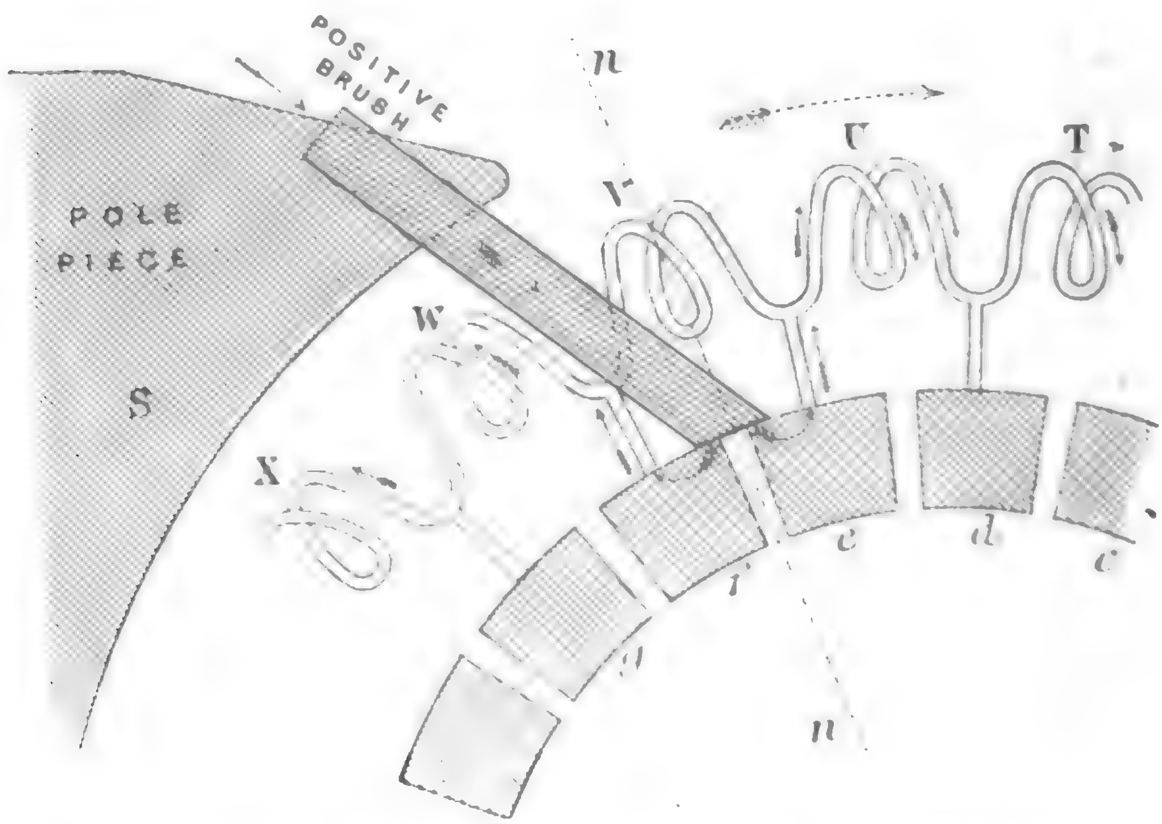


FIG. 334.—THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A MOTOR.

The cross-magnetizing force will also have the effect of weakening the field under the two leading pole-tips, and of strengthening them under the two trailing pole-tips. This is the opposite effect to that in a dynamo. In the motor (without lead even) the cross-magnetizing reaction tends to shift round the field in a sense *opposite* to that of the rotation. We shall now see what are the conditions for minimum sparking. Consider (Fig. 334) a coil W ascending on the left. The current in it is descending from the top brush, whilst it is itself the seat of an electromotive-force that tends

to stop or reverse its current. Now we know that the condition of non-sparking requires that at the moment whilst the coil passes under the brush, and is short-circuited, it should be passing through a field that is not only sufficiently strong, but one that tends to reverse the direction of its current. It is already in such a field; hence the act of commutation must take place *before* it passes out of this magnetic field. It must be commuted before it arrives at the highest point. In other words, a backward displacement must be given to the brushes if there is to be no sparking. The neutral line $n\, n'$ will therefore rake *backwards* in a motor into the fringe of the magnetic field. But since (in every case) both eddy-currents and hysteresis tend to shift the magnetic field slightly in the direction of the rotation—increasing the lead in a generator, diminishing it in a motor—it follows that the negative (or backward) lead in a motor may be slightly less than the positive (or forward) lead in a generator, for equal flow of current and equal excitation.[1] The advantage in point of weight of a motor in which the armature should help to excite the field-magnets, thereby reducing the weight of the latter, led Professors Ayrton and Perry,[2] in 1883, to advocate designs with weak field-magnets and powerful armatures acting with a forward lead. But from the foregoing considerations it follows that if a forward lead is given to the brushes of a motor in order to get a more powerful rotation, the motor will spark at the brushes, unless some special device, such as that used by Sayers, for the prevention of sparking, is employed. Minimum of sparking may be reconciled with high efficiency by so designing and constructing motors that the armature shall not perturb the magnetic field due to the field-magnets. This can be accomplished by following out the very same principles of design and construction which were found to be correct guides in the case of dynamos used as generators (p. 386). Mr. Sayers, whose method of winding armatures with auxiliary commuting coils

[1] This appears to be the explanation of the differences—otherwise unimportant—observed by Snell; *Journal Inst. Electr. Engineers*, xix. 194, 1890.

[2] *Journal Soc. Telegr. Engineers*, xii. May 1883.

was considered on p. 395, has applied the same method[1] to the armatures of motors. With this device the current flows through the armature sparklessly even though a considerable forward lead is given to the brushes; and in this way the armature is able to help the magnetization of the field-magnets. For description of a motor on this plan, see p. 540.

Mr. Mordey,[2] who has carefully tracked out the analogies between dynamos and motors, has observed that in several respects it is even more important that the rules laid down for the good design of generators should be observed for motors. Eddy-currents must be even more carefully eliminated. Also the greatest attention must be paid to proper mechanical arrangements for transmitting to the shaft the forces exerted by the field-magnet upon the armatures.

Contrast the conditions which are bound up in the disposition of the magnetic fields of the generator and the motor respectively. In one the armature is mechanically driven round while the magnetic forces in the field tend to pull it back. In the other, the magnetic forces of the field tend to drag it round, and it is thereby enabled to do mechanical work. In one case there is an opposing mechanical reaction tending to stop the steam engine. In the other there is set up an opposing electrical reaction (the induced counter electromotive-force) tending to stop the current.[3] In both cases the rotation is supposed to be taking place in the same sense—right-handedly. In both the effect is to displace the lines of force of the field, but in the generator the mechanical rotation acts as if it dragged the magnetism round, whilst in the motor the reciprocal magnetic reactions act as if they tried to drag round the armature, producing mechanical

[1] *Inst. Electr. Engineers*, xxii. 377, 1893; xxiv., 1895.

[2] *Phil. Mag.*, Jan. 1886.

[3] The law of the electrical reaction resulting in a generator from the mechanical motion is summed up in the well-known law of Lenz, that *the induced current is always such that by virtue of its electro-magnetic effect it tends to stop the motion that generated it.* In the converse case of the mechanical reaction resulting, in a motor, from the flow of electric energy, it is easy to formulate a converse law, viz. that *the motion produced is always such that by virtue of the magneto-electric inductions which it sets up it tends to stop the current.*

rotation. In the usual type of generator we found sparkless reversal to require a positive lead. In the motor, on the contrary, sparkless reversal necessitates a negative lead. If a motor is set with no lead, and if the field-magnets are very weak or are not excited at all, it will run in either direction according as it may be started. If in a motor with well-excited field-magnet the current be reversed in the *armature part* of the circuit only, the motor will usually reverse its rotation, but will usually require the lead to be reversed to run as sparklessly as before. If, instead of reversing the current in the armature, the magnetism of the field-magnet be reversed, a similar result will follow. If both are reversed at the same time, the motor will go on rotating as if nothing had happened.

Dynamos wound and connected for working as generators of continuous currents may be used in all cases as motors, but with some difference. A series dynamo set to generate currents when run right-handedly (and therefore having a forward right-handed lead), will, when supplied with a current from an external source, run as a motor, but runs left-handedly against its brushes. To set it right for motor purposes requires *either* that the connexions of the armature should be reversed, *or* that those of the field-magnet should be reversed (in either of which cases it will run right-handedly), *or* else the brushes must be reversed and given a lead in the other direction (in which case it will run left-handedly). A shunt-dynamo set ready to work as a generator will, when supplied with current, run as a motor in the same direction as it ran as a generator; for if the current in the armature part is in the same direction as before, that in the shunt is reversed, and *vice versâ*. A compound-wound dynamo, set right to run as a generator, will run as a motor in the reverse sense, against its brushes if the series part be more powerful than the shunt, and with its brushes if the shunt part be the more powerful. If the connexions are such (as in compound dynamos) that the field-magnet receive the sum of the effects of the shunt and series windings when used as a generator, then it will receive the difference between them when used as a motor. There are

certain advantages in using a differentially-wound motor, as will appear hereafter.

The subject of alternate-current machines as motors is treated separately in Chapters XXIV. and XXV.

Reversing Gear for Motors.—A motor, as will be seen from the preceding discussion, can be reversed by the operation of reversing the current through the armature, and at the same moment reversing the lead. But reversing the current can also be accomplished by rotating the brushes through 180°. Consequently both these actions may be accomplished by the single operation of advancing the brushes through $180° - 2\phi$, where ϕ is the original angle of lead. But as the brush would then slant in the wrong direction, it is usual to provide a second set of brushes. This is, indeed, Hopkinson's method of reversing. He employs two pairs of brushes, each pair being capable of moving about a common pivot, so that either the pair having a lead in one direction, or the pair having a lead in the other direction can be let down upon the commutator. The result of this arrangement is that, by moving a lever, the angular lead and the direction of the current are reversed at the same instant. Such reversing gears are obviously most useful in the industrial applications of motors, and if the difficulties of sparking at the brushes caused by the sudden removals of them from the collector be obviated, must prove much better than any mechanical device to reverse the motion by transferring it from the axle of the motor through a train of gearing to some other axle. One great advantage of electric motors is, that they can be easily fixed directly on the spindle of the machine which they are to drive; an advantage not lightly to be thrown away. Carbon brushes are almost always used for motors, as their position end-on is suitable for revolution in either sense.

Various other forms of reversing gear have been proposed to accomplish the desired end. If the field-magnets of a motor are so powerful relatively to the armature that no lead has to be given to the brushes, the rotation can be reversed by reversing the polarity of either part. In Immisch's larger motors, the reversing-gear, which is very substantial, removes one pair of brushes and puts down at the same diametral points a second pair, reversed in position and polarity.

The form of brush shown in Fig. 248*c*, p. 320, is designed by Holroyd Smith for motor work, as it allows of rotation in either direction. So also do carbon-brushes, such as Fig. 249, p. 321.

Another mode of reversing was suggested by the author[1] in 1882. It is indicated in Fig. 335. It consists in joining one of the brushes to a point half-way along the field-magnet coils, which, though connected across the mains as a shunt, must not be of very

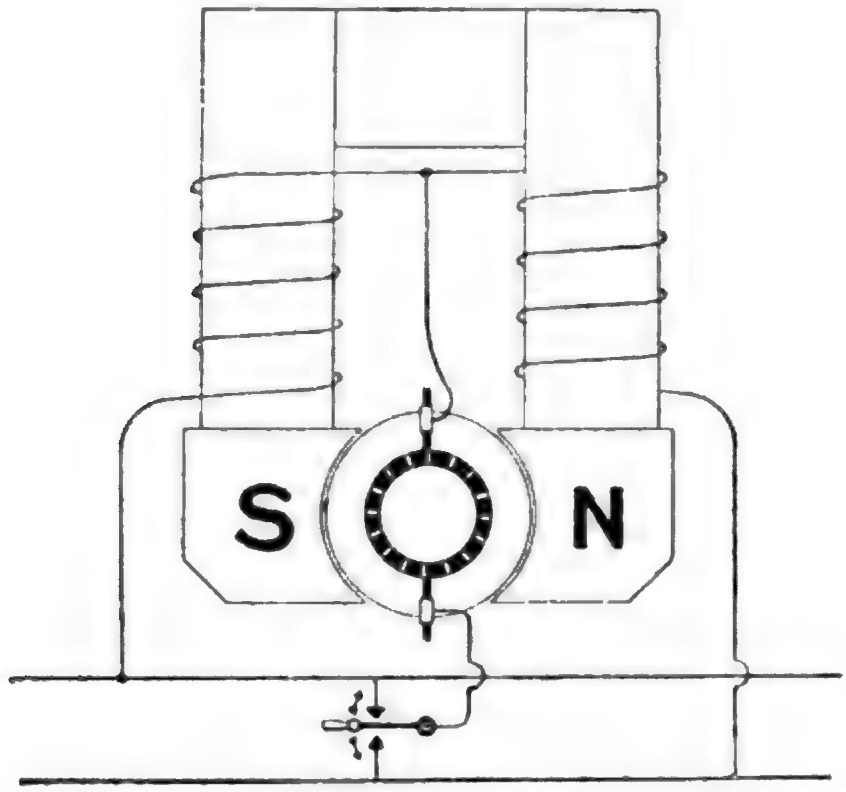


FIG. 335.—ELECTRIC REVERSING GEAR FOR A MOTOR.

high resistance. The current in the armature can then be reversed by simply switching the second brush from one main to the other. This principle is used in Maquaire's regulator for arc lamps, but is not suitable for large motors.

GOVERNMENT OF MOTORS.

It is extremely important that electric motors should be so arranged as to run at a uniform speed, no matter what their load may be. For example, in driving lathes, and many other kinds of machinery, it is essential that the speed should be regular, and that the motor should not "race" as soon as the stress of the cutting tool is removed.

Interruptor Governor.—One of the earliest attempts to secure an automatic regulator of the speed was that of

[1] Specification of Patent, No. 5122 of 1882.

M. Marcel Deprez, who in 1878 applied an ingenious method of interrupting the current at a perfectly regular rate by introducing a vibrating break into the circuit. The motor employed had a simple 2-part commutator, whose rotation timed itself to the makes-and-breaks of the current. This method is, however, inapplicable to large motors.

Centrifugal Governor.—Another suggestion, equally impracticable on the large scale, was to adopt a centrifugal governor to open the circuit whenever the motor exceeded a certain speed. A motor so governed runs spasmodically fast and slow.

It is also possible for a centrifugal governor to be employed to vary the resistance of a part of the circuit; for example, to work an automatic adjustment to shunt part of the current of a series machine from its field-magnets, or to introduce additional resistance into the field-magnet coils of a shunt-wound

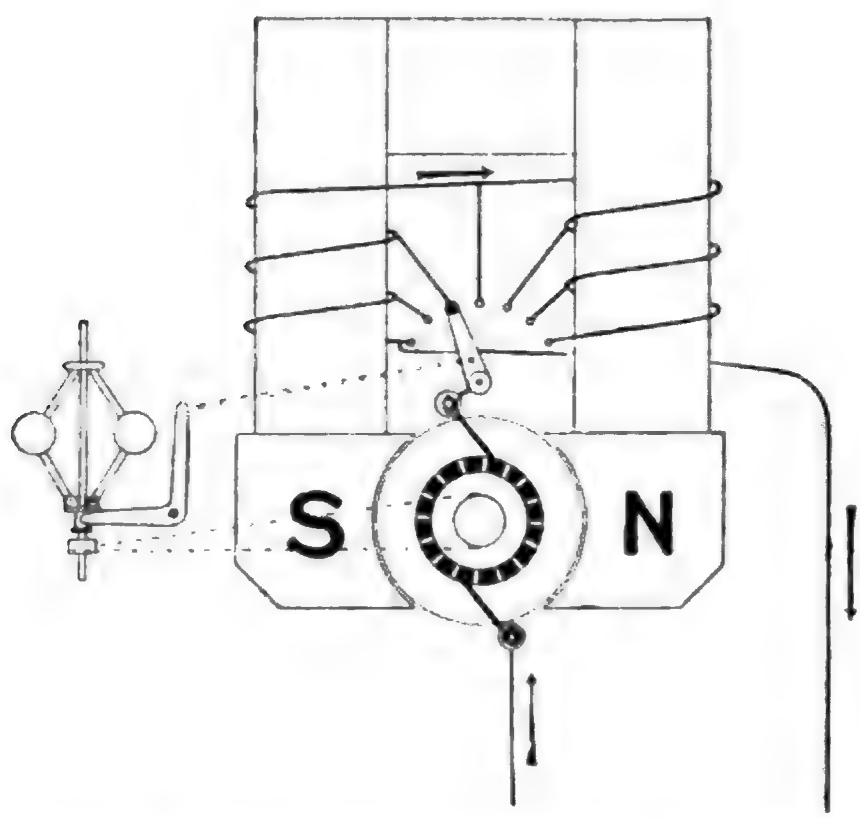


FIG. 336.—AUTOMATIC CENTRIFUGAL GOVERNOR.

machine, in proportion as the speed falls. A case is shown in Fig. 336, in which a centrifugal governor driven by the motor alters the number of exciting coils in the field-magnet circuit, causing the magnetism to increase if the motor runs

too fast, and so brings down the speed again. This method was proposed by Brush, and answers well for motors in series in arc-light circuits.

Periodic Governor.—Ayrton and Perry proposed several forms of "periodic" centrifugal governor, a device by which in every revolution power is supplied during a portion of the revolution only, the proportion of the time in every revolution during which the power is supplied being made to vary according to the speed. As the main difficulty with such governors is to prevent sparking they are only applicable to very small motors. But there is a still more radical defect in all centrifugal governors: they all work too late. They do not perform their functions until the speed has changed.

Dynamometric Governors.—The author devised[1] another kind of governor which is not open to this objection. He proposed to employ a dynamometer on the shaft of the motor to actuate a regulating apparatus, consisting, either of a periodic regulator to shunt or interrupt the current during a portion of each revolution, or of an adjustable resistance connected in part of the circuit. The dynamometric part may take the form of a belt dynamometer (such as Alteneck's) or of a pulley dynamometer (such as Morin's or Smith's). In the latter case, which is the more convenient, a loose pulley runs on the motor shaft and is connected by a spring arrangement with a fixed pulley. The rotation of the motor will drag round the fixed pulley in advance of the loose pulley, and the angular advance will be proportional to the torque. The amount of such angular advance determines the action of the regulating part. The regulator in this case is therefore worked not according to the speed of the motor, but according to the load it is carrying. Any change in the load will instantly act on the dynamometric governor before the speed has time to change. If such a governor is purposely over-set it may even have the effect of causing the motor to run faster when the load comes on than it does when running idle.

Electric Governing.—Another method of governing, not

[1] Specification of Patent, No. 1639 of 1883.

requiring any rotating parts, has been proposed by the author. He uses as field-magnets a double set of poles, set at different angles with respect to the brushes of the motor. One pair of magnetic poles, having a certain lead, is actuated by series coils, the other pair, having a different lead, by shunt coils (see Fig. 265*c*). When both shunt and series are working, there will, of course, be a resultant pole having some intermediate lead. If the load of the motor is diminished it will tend to run faster, increasing the current in the shunt part, decreasing it in the series part, and therefore altering the effective lead and preventing the increase of speed.

In 1880 a motor was patented by André in which the field-magnets were wound in two separate circuits, one of thick and the other with thin wire, the current dividing between them, and the armature was connected as a bridge across these circuits as the Wheatstone's bridge. Motors governed on this principle were constructed about 1884, by Lieut. F. J. Sprague; they show remarkably good regulation.

The method of automatic regulation that is most perfect in theory is undoubtedly that of Professors Ayrton and Perry,[1] and is expounded in the following pages; it results in a differential compound winding.

THEORY OF SELF-GOVERNING MOTORS.

In the chapter on Self-regulating Dynamos, on pp. 224 to 242, were set forth the methods of solving the problem how to arrange a dynamo so that it shall feed the circuit with electric energy under the condition of a constant pressure, when driven at a constant speed. The solution to that problem consisted in the employment of certain combinations which gave an initial magnetic field due to a shunt coil, and an increment to that field dependent on the current that might be flowing in the main circuit.

Now it is not hard to see that this problem may be applied

[1] *Journal Soc. Telegr. Engineers*, vol. xii., May 1883; see also a later paper in *Phil. Mag.*, 1888.

conversely, and that motors may be built with a combination of arrangements for their field-magnets, such that, when supplied with currents under the standard conditions of constant pressure in the mains, their speed shall be constant whatever the load. It will be evident, without any numerical calculations, that the windings must oppose one another—one must tend to magnetize the field-magnet, the other to demagnetize. Take the case of a shunt motor supplied at a constant potential $\mathcal{E}$, and running at a certain speed with a certain load. If the load is suddenly removed the motor will begin to race, its racing will increase the counter electromotive-force developed and will partly cut down the armature-current. But the decrease of current will not be quite adequate to bring back the speed, because of the internal resistance of the armature, which has prevented the whole energy of the armature current from being utilized as work. A demagnetizing series coil wound on the field-magnet will, however, effect what is wanted, for then, with any reduction of load, the corresponding reduction of current can take place, the resulting increase in the field-magnetism being sufficient to get the required larger counter electromotive-force without any increase in speed. For constant-current distribution no method of compound winding, whether differential or additive, has been found satisfactory; special regulators must be employed.

The following synoptical table contrasts the arrangements for self-regulating generators with those of self-governed motors :—

GENERATOR.		MOTOR.	
Given Constant Speed.		*To get Constant Speed.*	
To get e *constant.*		Given $\mathcal{E}$ *constant.*	
Initial magnetism	Steel magnets. Separate excitation. Shunt coils.	Initial magnetism	Steel magnets. Separate excitation. Shunt coils.
+ Series-regulating coils.		— Series-regulating coils.	

In discussing the theory of the self-governed motor, we shall follow the same general lines as in discussing the theory

of the self-regulating generator, namely, find an equation expressing the desired condition of constancy.

Shunt or Separately-excited Motor with Series-regulating Coil.—Using the same notation as previously, we have for the counter electromotive-force developed in the armature—

$$E = n Z \mathsf{N};$$

also

$$E = \mathcal{E} - (r_a + r_m) C.$$

Now N is made up of two parts, viz.:—N_1 the permanent part (which in a shunt motor is equal to $q S_s C_s$, where S_s is the number of windings in the shunt), and another part depending on the series coil which we may write $q S_m C$, where S_m is the number of windings in series and q has the same signification as on p. 229, and is equal to 4π divided by ten times the sum of the magnetic reluctances. Its value therefore depends upon the permeability, and therefore upon the degree of saturation of the iron of the magnetic circuit. Reserving this point for further consideration, we may write

$$\mathsf{N} = \mathsf{N}_1 - q S_m C.$$

If we had written + instead of −, we should find the solution coming out with the negative sign, indicating that the windings must be so arranged that the current in the series coil circulates in the negative or demagnetizing sense. We write the negative sign, however, as we already know that this must be so. We also assume at present that there are no armature reactions. Substituting the value of N in the fundamental equation, we have

$$E = n (Z \mathsf{N}_1 - Z q S_m C);$$

and equating this to the other value of E in the second equation above, we find

$$n = \frac{\mathcal{E} - (r_a + r_m) C}{Z \mathsf{N}_1 - Z q S_m C}. \qquad \text{[I.]}$$

Having thus obtained an expression for the speed, we must examine the various parts of the expression to see which

are variable and which constant, and so deduce a relation which shall make n constant. Now in both numerator and denominator there are two terms, the first of which is a constant, whilst the second of each contains the variable C. A little consideration will show that the fraction cannot have a constant value unless the two coefficients of the variable in the second terms bear the same ratio to one another as do the two constants which stand as the first terms; or n cannot be constant unless

$$\frac{\mathcal{E}}{Z\,N_1} = \frac{r_a + r_m}{Z\,q\,S_m},$$

or

$$\frac{\mathcal{E}}{N_1} = \frac{r_a + r_m}{q\,S_m}, \qquad [II.]$$

which is the desired equation of condition.

If this condition be observed (and it will be noted that the quantity of series winding required is proportional, as in the self-regulating dynamo, to the internal resistance of the machine), then the speed will be constant and of the value

$$n = \frac{\mathcal{E}}{Z\,N_1} = \frac{r_a + r_m}{Z\,q\,S_m}. \qquad [III.]$$

From the first of these relations we see that the speed at which the machine is thus governed to run is the same speed as that at which, if driven as a generator on open circuit, it will yield an electromotive-force equal to that of the supply at the mains. When running as an unloaded motor, it ought of course to turn so fast as to reduce the current through its armature to a minimum, which it can do by running at this speed. It is evident that by making the permanent part of the magnetism strong enough, the critical speed—that is to say, the speed for which the motor is self-governing—may be made as low as desired. As the load on the motor is increased, the flow of current through the armature must be increased, and this increased current cannot flow unless in some way the counter electromotive-force of the armature be diminished. As the speed is to be kept up, this is

accomplished by the lowering of the magnetism, which occurs in consequence of the increased current flowing through the demagnetizing coils. The quantity denoted by q, which depends on the permeability of the iron, may be taken at an average value between the two extremes which it has at maximum load and at zero load, since in a well-designed motor the resistances in the armature-circuit are very small, and the efficiency as a whole high, the demagnetizing effect of the series coils, even at full load, need only reduce the magnetization by a small percentage. Moreover, with the backward lead given to the brushes to prevent sparking, the armature itself will act partially as a demagnetizing series coil, and so compensate for alteration in the permeability. The magnetism is a maximum when the motor is running empty. When the load is greatest, if the motor is running at, say 80 per cent. efficiency, E will be 80 per cent. of $\mathcal{E}$; that is to say, N will be 80 per cent. of N_1. It is between these limits in the magnetization that the value of q must be averaged. It is evident from equation [III.] that if the motor is already provided with a given series winding, there can be found a value of $\mathcal{E}$, for which the condition of self-governing can be still fulfilled. In the case of a shunt motor the above equation is capable of further simplification; for we know that $\mathcal{E} = C_s r_s$, where r_s is the resistance of the shunt, and $N_1 = q\, S_s C_s$. Substituting these values in [II.] above, we get

$$\frac{S_s}{S_m} = \frac{r_s}{r_a + r_m}, \qquad \text{[IV.]}$$

which is Ayrton and Perry's rule for the winding of the self-governing motor. Motors wound differentially in the proportion indicated in equation [IV.] are very nearly self-governed. Some excellent motors by Sprague were wound according to this rule. One very curious property of this method of winding is as follows:—Suppose the motor to be standing still and the current turned on, the ampere-turns due to the shunt will be equal to $\mathcal{E}\, S_s \div r_s$, whilst those due to the series coil will be $\mathcal{E}\, S_m \div r_a \times r_m$; and these, according to

equation [IV.], will be equal, and they are of opposite sign. There should then be no magnetism excited at all. But if there is any lead at the brushes, the magnetizing tendency of the armature will come into play; and if the brushes have a considerable negative lead, the effect will be to magnetize the field-magnet in the wrong sense, and then the motor starts the wrong way. The defect might be remedied by cutting out the series coil or reversing it, until the motor has got up its speed. The latter course is preferable, as the additional torque of the series motor is of great advantage in overcoming the statical resistance to motion experienced at starting.

It is obvious that the number of shunt-turns should theoretically be such that the motor, driven on open circuit at the given speed, shall generate an electromotive-force equal to $\mathcal{E}$.

Practical Determination of the Shunt and Series Windings.[1]—As in the case of compound windings of dynamos (p. 238) so for motors, the proper windings can be found by simple experiments, a temporary coil being wound and separately excited, and a resistance equal to the future r_m being added to the armature resistance. Two experiments are required. Run the motor first with no load at the brake, using the proper pressure V, and excite the temporary coil, observing the number of ampere-turns that are needful to bring the speed down to the required n. The number of ampere-turns in this case is equal to $S_s C_s$, where C_s is the current, which economy dictates should be used in the shunt. Secondly, run the motor with its fullest load at the brake, and again excite the field-magnet with such a number of ampere-turns that the speed is constant at n. From this and the previous experiment S_m can be calculated.

The efficiency of a differentially-wound motor cannot be expected to be quite as high as that of one which is not differentially wound, since the energy expended in the former case in magnetizing the field-magnets is greater relatively to the amount of magnetization produced.

[1] It should be pointed out that this process differs from that suggested by Professors Ayrton and Perry in their paper on electromotors, in *Journal Soc. Teleg. Engineers*, May 1883. Their method depends on the volume left on the bobbins of the field-magnets, which is assumed to be constant.

MECHANICAL CHARACTERISTICS OF COMPOUND DIFFERENTIAL MOTORS.

It may be convenient here to consider the graphic representation of the regulations between speed and torque in motors provided with mixed windings.[1]

The curves for constant-potential supply are shown in Fig. 337. The letters M and S refer to main circuit windings and

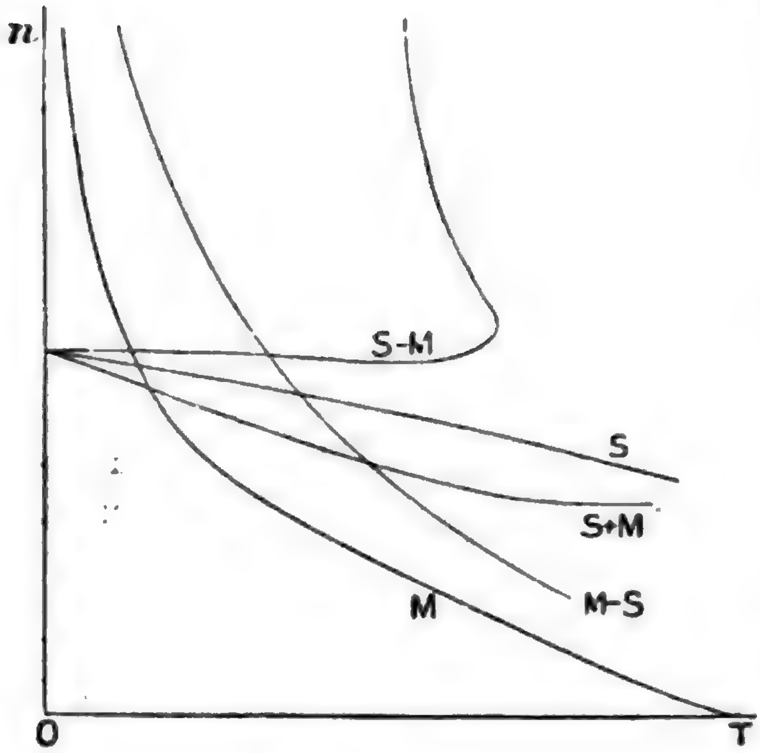


FIG. 337.
MECHANICAL CHARACTERISTICS AT CONSTANT POTENTIAL.

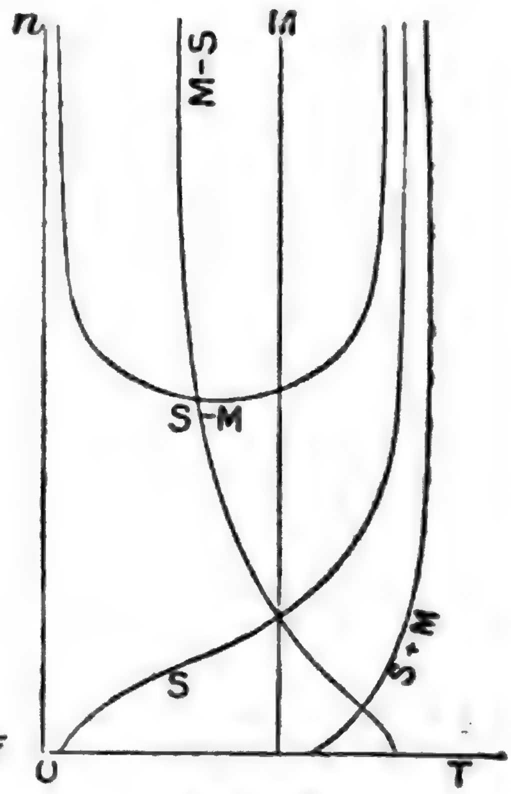


FIG. 338.
MECHANICAL CHARACTERISTICS WITH CONSTANT CURRENT.

shunt windings respectively. The forms of the curves for mixed windings differ somewhat according to the proportions of the two sets of coils. The important case is that of the differential winding marked S − M, having a few series turns to correct the droop of the pure shunt-winding, and it will be noted that up to a certain limit the speed is nearly constant, but that there is a maximum value to the torque. In the case of constant-current supply, as the curves of Fig. 338

[1] The author is indebted to Frölich's *Die Dynamoelektrische Maschine* for the curves of motors with mixed windings. Similar curves have been deduced by Rechniewski, see *Séances de la Société de Physique*, 1885, p. 197.

show, the only winding which gives any approximation to a constant speed is the differential winding with large shunt and small series coil. For, as in the case of the constant-current generator, the variation of the magnetism has to be carried through an enormous range, defying any averaging of the magnetic permeability.

An elegant graphic method of treating the problem of self-government of motors is given by M. Picou in *La Lumière Électrique*, xxiii. 114, 1887.

Shunt Motor.—It was observed by Mr. Mordey,[1] that if a pure shunt motor is constructed upon perfect designs—that is to say, having very small resistance of armature and very large resistance of shunt, and having also field-magnets, which are very powerful relatively to the armature, and an armature properly laminated and sectioned so as to reduce eddy-currents and self-induction to a minimum—such a shunt dynamo, if supplied from mains at a constant potential, will run at a nearly constant speed whatever the load.[2] The slight demagnetizing action of the armature when a negative non-sparking lead is given to the brushes acts, in fact, instead of any special demagnetizing coil. The following tests showed a constancy to within 1½ per cent. for all loads within working limits.

Potential at Terminals.	Current (amperes).	Horse-power at Brake.	Revolutions per Minute.	Torque (pound-feet).
68·4	44	1·1	1125	5·15
68·4	126	7·4	1120	33·4
68·4	165·5	10·36	1115	48·8
68·4	180	11·14	1110	53·0

With a lower electromotive-force the same motor regulated almost equally well, but at a lower speed. It was observed that, especially when the motor was giving out small horse-power, the speed was increased by weakening the field.

[1] See *Phil. Mag.*, January 1886.

[2] This might have been foreseen from the equations of p. 525, in which if $r'' + r''' = 0$, the condition of regulation will give $S_m = 0$.

2 M

Other Methods of Governing Motors.—A further suggestion for governing motors is due to Mr. Mordey and Mr. C. Watson. They wind the armature with two windings, having separate commutators. One winding—the main one—is the ordinary armature circuit of the motor, and is supplied with current from the external source, causing the armature to revolve. The other winding, which may be called the regulating armature winding, is small in amount, and is disposed over, or side by side with, the main motor-winding. This additional winding is not connected to the mains or source of current, but to the field-winding by means of a special commutator or collector and brushes. It will be observed that this additional armature-winding, revolving in the field, constitutes a generator of current. The regulating action is as follows:—When a tendency to increase in speed results from a diminution of the load, the additional armature-winding tends to increase the strength of the field by supplying more current to the field-coils, and thus raises the opposing electromotive-force of the motor, diminishes the amount of current received from the mains, and so reduces the speed to its normal rate. Again, an increase of the load, tending to reduce the speed, is counteracted by a lessening of the magnetizing current produced by the additional winding, a consequent lowering of the opposing electromotive-force of the motor, and an increase of the current received from the mains. It will be seen that as this plan is summative it does not require so great an expenditure of energy in the fields as a differential winding: nor is it open to the objection that the motor may start in the wrong direction. On the otherhand, it has the drawback of requiring an additional commutator. The method has given very good results.

A possible mode of governing constant-current motors is by providing a variable magnetic shunt, in the converse of the manner suggested by Trotter for constant-current generators. Various other modes[1] of controlling the speed by altering the magnetism have been suggested, but few of them are automatic or reliable.

[1] See a most interesting and fully illustrated paper by F. B. Crocker in *Electrical World*, xiii. 311, 1889.

CHAPTER XXI.

MODERN FORMS OF CONTINUOUS-CURRENT MOTORS.

ALMOST any good modern dynamo (independently excited, shunt wound, or compound wound) will serve as a motor on mains supplied at the proper pressure; but attention has to be paid to the setting of the brushes that it may run rightly, and the machine so used must be one that will give the proper voltage at the proper speed. In designing motors precisely the same principles hold good[1] as obtain for designing generators; for the same features, namely, low internal resistance, powerful field-magnets, and proper elimination of eddy-currents, which go to make a good generator, also apply to the making of a good motor. For example: suppose it is desired to design a 10 H.P. motor to run at 500 revolutions per minute, when supplied from 200 volt mains. Now 10 H.P. is 7460 watts; a motor to give out actually 7460 must be allowed to absorb (at 85 per cent. nett efficiency) 8776 watts. Further, if its electrical efficiency is to be, say 90 per cent., it must generate 180 volts of counter electromotive-force. Dividing 8776 watts by 180 volts we find 48·75 amperes as the current it must take at normal load. If, therefore, we simply set to work to design a dynamo with good powerful field-magnets capable of generating 50 amperes at 180 volts at a speed of 500 revolutions per minute, we shall have obtained what we wanted.

Snell has given the following rules for expressing the actual H.P. which may be safely and continuously taken from continuous-current motors:—

Ring armatures, 2-pole; H.P. $= 0·00001 \times l d^2 n$,
Drum armatures, 2-pole; H.P. $= 0·000015 \times l d^2 n$;

---

[1] For discussion of the subject of motor design, see a paper by Snell in *The Electrician*, xxii. 313 and 403, 1889; also *Journ. Inst. Electr. Engineers*, xx. 1891.

where l is length of armature and d its diameter, in inches, and n the revolutions per minute.

It might be supposed from the opening statement that any description of motors was superfluous. There are, however, certain special forms of machine that have come into notice as motors, and are, therefore, described here.

Amongst the motors which were at one time in commerce were special forms by Ayrton and Perry, with a fixed external ring armature and an internal revolving field-magnet. They possessed the structural defect of possessing too weak a field-magnet to enable them to run sparklessly, and though remarkably compact and convenient, fell into disuse. These motors were illustrated in the earliest editions of this book. A little later excellent forms up to several horse-power were constructed by Reckenzaun, Immisch and others, which were

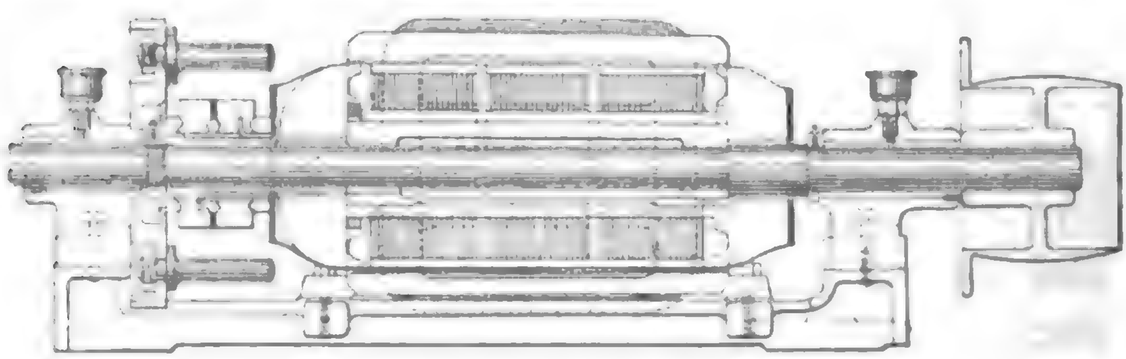


FIG. 339.—IMMISCH'S MOTOR (Section).

also noticed in former editions. Reckenzaun conceived the useful notion of winding the magnets of a series motor for traction purposes with two, or in some cases three, coils on each limb, which might be put in parallel or series so as to vary the exciting power and permit of obtaining the different rates of speed and power required in tramway work, without resorting to artificial resistances, and also of obtaining a great torque in starting, when all the coils are in series.

Immisch's motors were amongst the first in England to be well and mechanically constructed. The armature cores were built up of insulated disks, having at the ends, and at intervals, thicker disks provided with projecting driving-teeth, all the disks being securely keyed to the shaft. The windings were insulated with Willesden paper protected with

india-rubber varnish. In the commuting arrangements special means were taken to cut out the coils as they reach the neutral point; the effect, according to the inventor, being to diminish cross-magnetizing influences and obviate changes of lead.

In Immisch motors carbon brushes, Fig. 249, p. 321, are used. The mode of driving the core-disks of the large machines is shown in Fig. 224, p. 294.

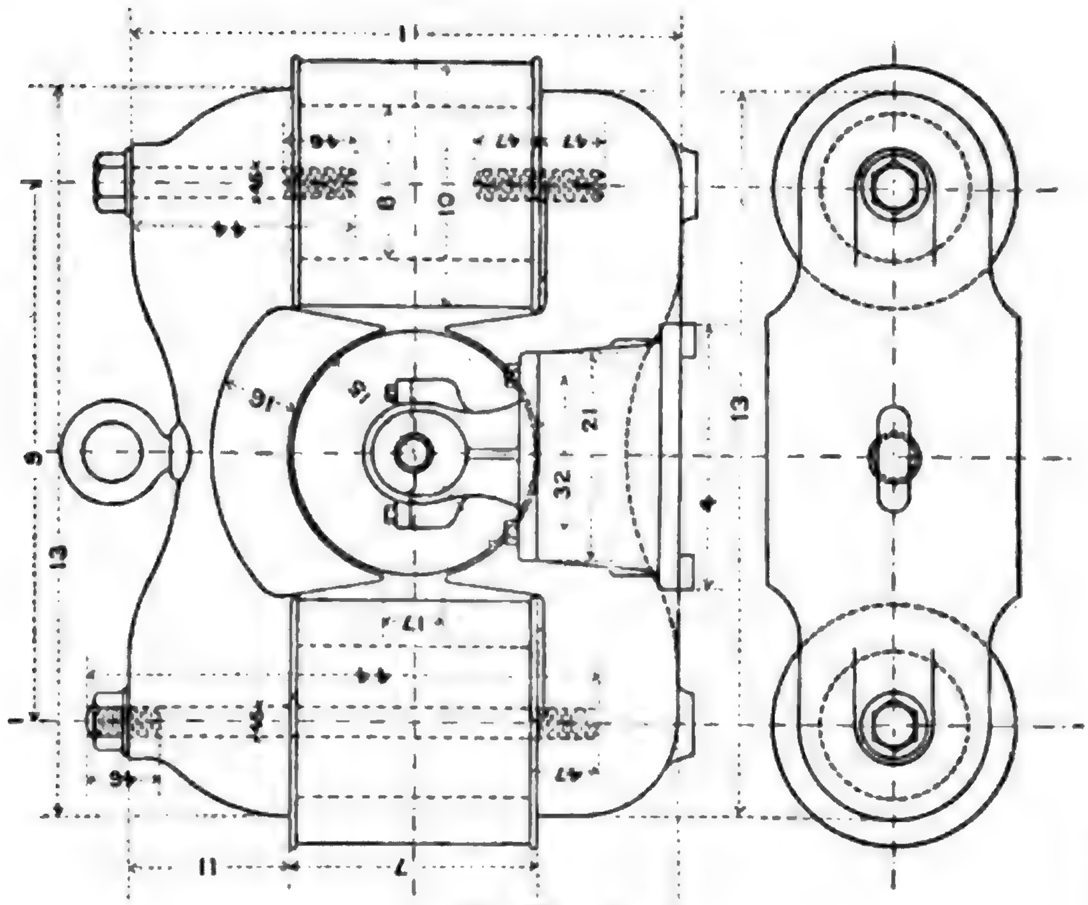
A 30-H.P. motor, designed by Mr. A. T. Snell, for mining purposes,[1] weighing 850 kilogrammes, gave the following results :—

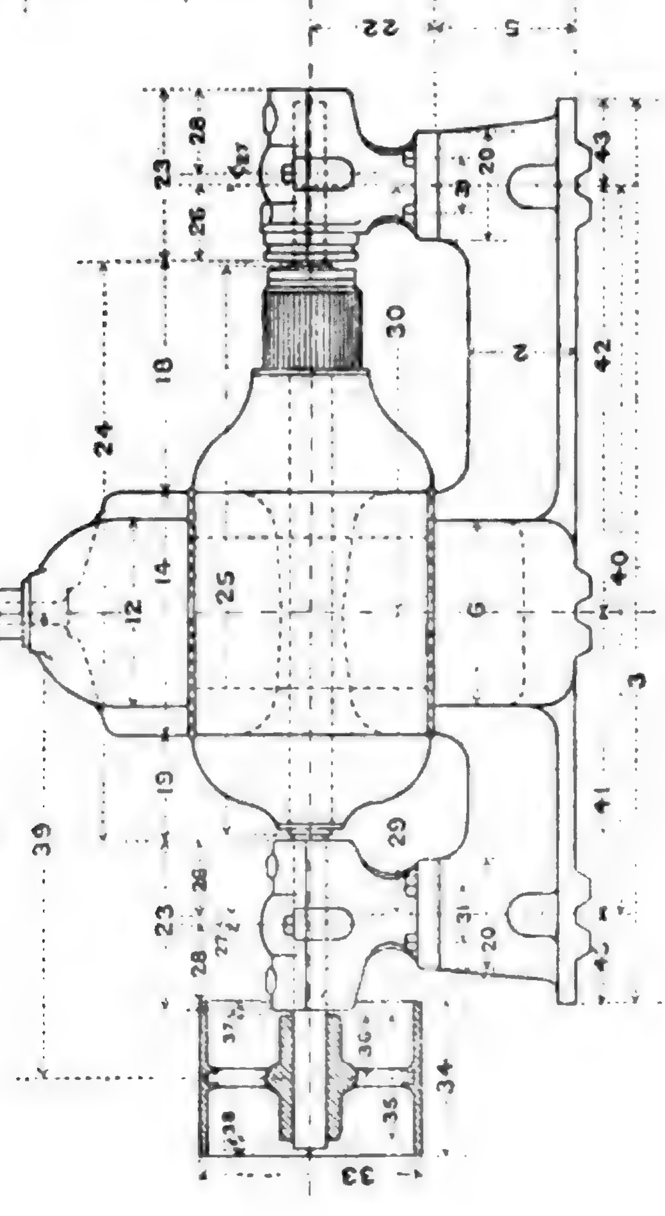
Revolutions per Minute.	Volts.	Amperes.	E.H.P. absorbed.	H.P. given out.	Efficiency.
660	500	49	33	29·8	·90
680	500	48	32·2	29·5	·91
675	500	49	33	29·5	·89

A number of firms—for example, Messrs. Cuttriss of Leeds, M. Trouvé of Paris, and Messrs. Crocker and Wheeler, in New Jersey—have made a speciality of small motors for driving fans, lathes and other light running machinery.

All large firms who construct continuous-current dynamos, furnish them also as motors, in some cases making special patterns, the only difference being that a machine designed for a motor usually has the field-magnet carried to a rather higher degree of saturation, and made relatively more powerful than in the corresponding size of dynamo. If two machines are to be used together as generator and motor, the former being driven at a constant speed, the latter will not run at a constant speed at all loads if they are of identical construction, for the voltage given to the motor falls as the current in the line increases. To make the motor run at constant speed it should be wound with fewer armature conductors in proportion precisely to the efficiency contemplated.

[1] See notes by Mr. Snell on Electrical Work in Mines, in *Proc. South Wales Institute of Engineers*, July 27, 1891. Also lecture on *Electricity in Mining*, by author of this book, published by Messrs. Spon.





The figures refer to the first column in the table opposite, where the dimensions of the part in question are given in inches for machines of various output.

FIG. 340.—SPRAGUE'S MOTOR.

TABLE OF DATA OF SPRAGUE MOTORS.

(The figures in the first column refer to dimensions indicated in Fig. 340).

Motor H.P.		1	2	3	5	10	15	20	25	35	50	75
Total height	1	11 3/4	13 3/4	15 7/16	17 3/4	20 3/8	22 7/8	25 1/4	28	33 7/8	38 1/4	48 1/8
Height of bed-plate ..	2	2 3/8	2 3/4	3	3 1/2	4	4 1/4	4 1/2	5 1/4	7 1/2	8 5/8	9
Length of bed-plate ..	3	19 1/2	22 5/8	26 3/4	28 1/4	31 3/4	37 1/2	40	45 3/4	57 3/4	64 1/2	73 1/8
Width of bed-plate ..	4	5 3/4	6 3/4	7 1/4	8	8 7/8	9 1/4	10 1/2	12 1/4	13 1/2	14 3/4	19
Height of core-seat ..	5	3	3 1/4	3 3/4	4 1/2	5	5 1/4	5 3/4	6 1/2	7 7/8	10	13 1/4
Diam. of core-seat ..	6	4	4 7/8	5 1/2	5 7/8	7 1/2	8 1/2	9 1/4	10 3/8	13 1/8	14 3/4	17 1/2
Length of core	7	5 3/8	6 5/8	7 3/16	8 1/4	9 3/4	10 5/8	11 3/4	13	15 1/4	17 1/4	19 7/8
Diam. of core	8	3 1/4	3 3/4	4 3/4	4 5/8	6	6 13/16	7 3/4	8 1/2	10 3/8	11 3/4	13 1/2
Between core-centres	9	12 1/2	14 3/4	16 3/4	19 1/4	22 3/4	24 7/8	26 3/8	30 1/2	32 1/4	36 3/4	43 1/4
Diam. over winding ..	10	6 3/8	6 3/4	8	9 1/8	10 1/4	12	12 3/4	14 1/4	15 1/4	17 1/4	20 1/4
Height of keeper ..	11	3	4	4 1/2	5	6 1/4	7	7 3/4	8 1/2	9 3/4	11	15
Width of keeper ..	12	4	4 7/8	5 1/2	5 7/8	7 1/2	8 1/2	9 1/4	10 1/8	13 1/4	14 3/4	17 1/2
Length of keeper ..	13	16 1/2	19 3/8	22 1/4	25	29 7/8	33 3/8	35 7/8	40 3/4	45 7/8	51 1/2	60 3/4
Length of field	14	5 1/4	6 1/4	7	8	9 1/4	10 3/8	11 3/8	12 3/4	14 1/4	16	18 1/2
Bore of field	15	5 3/8	6 5/8	7 3/16	8 1/4	9 3/8	10 3/8	11 3/4	13	15 1/4	17 1/4	19 7/8
End thickness, pole-piece	16	1 3/4	1 7/8	2	2 1/4	3	3 1/4	3 1/2	3 1/2	3 5/8	3 3/4	4
Space between pole-tips	17	1 3/8	1 1/2	1 7/8	2 1/8	2 7/16	2 3/4	3 1/4	3 3/8	4 3/4	5 3/8	5
Block to fields (comm. end)	18	5	5 7/8	7 3/4	8 3/16	8 5/8	11 5/16	11 5/16	12 1/4	17 9/16	19 1/4	20 3/4
Block to fields (pulley end)	19	2 1/4	2 7/8	3 3/4	3 5/16	3 9/16	4 1/16	4 1/16	5	8 11/16	9	10 3/4
Length, pillow-block seat	20	2 3/8	2 3/8	3	3 1/4	3 3/8	3 3/4	4 1/2	5	5 1/2	6	7
Width, pillow-block seat	21	4 1/2	5 1/4	6	6 1/2	7 3/8	7 3/4	9	10	11	12	12 1/4
Height of pillow-block	22	2 11/16	3 5/16	3 19/32	4 1/8	4 11/16	5 5/16	5 7/8	6 1/2	7 5/8	8 5/8	11 1/4
Length of pillow-block	23	3 3/4	4 1/4	4 1/2	5 1/4	6	6 3/8	7 3/4	8 3/4	10	11 3/8	14 1/2
Between shaft shoulders	25	12 7/16	14 15/16	18 7/16	19 3/8	21 3/16	25 5/8	26 3/8	30 3/4	40 3/8	45 1/2	51 3/16
Diam. of pulley	33	4 1/8	5	6	8	9	10	11	12	16	20	24
Face of pulley	34	2 1/2	3	3 1/2	4	6	7	8	10 1/2	12	12	13
Length of hub	35	2 1/4	2 3/4	3	3	3 3/4	4 3/4	5 1/4	6	9	9	9
Between centre of motor and centre of pulley	39	9 13/16	11 13/16	13 7/16	14 1/4	16 3/16	18 1/4	20 3/8	23 3/8	30 3/4	32 3/8	38 11/16
Length of core bolts ..	44	11 1/8	13 1/8	14 3/8	16 1/2	19 1/4	21 5/8	23 3/8	25 1/2	13	14 3/4	21
Diam. of core bolts ..	45	5 5/8	3/4	7/8	1	1 1/8	1 1/4	1 1/4	1 1/4	1	1 3/8	1 3/4
Diam. of core disks ..	48	4 3/4	5 13/16	6 5/16	7 1/4	8 1/4	9 3/4	10 1/4	11 13/16	14 1/4	16	18 1/2
Diam. of armature ..	49	5 1/4	6 1/2	7 1/16	8 1/8	9 1/4	10 1/2	11 3/8	12 7/8	15 1/16	17 1/16	19 5/8
Armature conductors (at 110 volts)	50	768	432	432	348	..	..	..	..	..	..	..
Armature conductors (at 220 volts)	50	1680	1248	900	696	576	352	320	320	..	..	..
Armature conductors (at 440 volts)	50	..	..	..	..	1080	704	640	600	464	420	388
Segments in commutator	51	24	48	36	58	{48, 90}	88	80	{80, 100}	58	70	97
B in core disks ..	52	3820	3770	4090	4040	4770	4720	4740	4240	8100	7030	7720
N (useful) megalines ..	53	·489	·701	·924	1·228	1·800	2·413	2·974	3·274	8·517	9·353	13·943
Total ampere-turns ..	54	5298	7746	8192	12043	11535	14814	17453	22475	28138	24973	31700
Revolutions per min...	55	1750	2000	1650	1550	1360	1500	1350	1350	675	665	485

For instance if the electrical efficiency of the transmission is to be 85 per cent. the motor armature should have 85 per cent. of the number of conductors that there are in the generator armature. As an example see Brown's 240 H.P. motor mentioned on p. 412.

Sprague's Motors.—Several firms have made a speciality of motor work. Amongst American engineers, Lieut. F. J. Sprague was early in the field with several forms of motor of excellent design and construction; many hundreds of them were in use in the States for lifts, machine tools, and the like, until his firm was amalgamated with the Edison Co., after which time the Edison bipolar dynamo was substituted. One form of these machines, resembling the "Manchester" type of dynamo, is shown in Fig. 340. Sprague's method of winding the field-magnets with a differential compound winding is identical with that invented in 1883 by Ayrton and Perry, depending upon the use of a coil in series with the armature to demagnetize and weaken the field.[1] Many other ingenious methods of governing and practical applications have been worked out by Sprague. The reference numbers given in Fig. 340 relate to the statistics given in the accompanying table, from which the relative sizes of a well-worked-out line of machines can be learned. For further details the reader is referred to the accounts published in the technical press.[2]

Crocker and Wheeler's Motors.—Another American firm that has been very successful with motors, particularly in small sizes, is that of Crocker and Wheeler, of Ampere, N.J.

Fig. 341 gives a general view of the bipolar motor of this firm. The magnet limbs are stamped in one piece out of wrought iron or mild steel, and set firmly in the cast-iron bed. The armature is built up of toothed core plates (see Fig. 212, p. 287) and ring wound, the finished armature being represented in Fig. 342. A starting gear is usually provided with

[1] See Specifications of British Patents, Nos. 15,768 of 1884, and 3524 of 1885.

[2] *Electrical World*, October 1886; also Martin and Wetzler's treatise on *The Electric Motor*, 157–75; and *Electrical World*, xiv. 3, 1889; xv. 370, 1890; also *Electrician*, xxiv. 248, 1890.

these motors, consisting of a switch, with resistances, so arranged that the field-magnet is first excited, the armature then thrown into circuit with a resistance which, when the

FIG. 341.—CROCKER-WHEELER MOTOR.

motor acquires speed is cut out by a further movement of the starting switch. For use in arc-light circuits[1] a centrifugal governor is added to the shaft. For sizes up to 10 H.P. the

FIG. 342.—ARMATURE OF CROCKER-WHEELER MOTOR.

bipolar type is used, but for large sizes 4-pole designs of the type of Fig. 278 are preferred.

The following table gives some statistics about these machines.

For further accounts of the Crocker-Wheeler motors, and

[1] For some accounts of motors for constant-current circuits, see *Electrical World*, xv. 269, 1890; xvii. 120 and 130, 1891; also *Electrician*, xxv. 16, 45 and 131, 1890.

CROCKER-WHEELER MOTORS.

Output.	Revolutions per Minute.	Weight, Lbs.	Armature Diam., Inches.	Commutator Parts.	Core Teeth.
Bipolar.					
$\frac{1}{12}$	1900	17	3	12	0
$\frac{1}{8}$	1800	26	3·601	16	8
$\frac{1}{4}$	1400	70	4·75	24	12
$\frac{1}{2}$	1250	106	5·625	24	12
1	1000	201	7	32	16
2	1000	281	7·75	48	24
3	950	364	8·75	48	24
5	950	590	9·187	56	28
10	875	1065	11	56	28
Four-Pole.					
15	850	1450	11	102	51
30	750	2800	15	110	55

their application to driving workshop tools, the reader is referred to the technical journals.[1]

A.E.G. Motors.—In Germany the Allgemeine Elektricitäts Gesellschaft has made a specialty of small motors, both for continuous current and alternating. Their typical form up to 12 H.P. is shown in Fig. 343. For larger outputs 4-pole and 6-pole machines are used. This company has long systematized its manufactures. The following table includes the usual sizes.

H.P.	$\frac{1}{10}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1	1·5	2·5	4	6	10	20	30	40	60	90
Revs. per minute	1600	1100	2100	1900	1650	1480	1270	1100	1020	925	850	720	650	600	450
Total wt., kilos	30·5	50·5	55	75	120	220	355	385	520	825	1820	2370	2980	4100	4760
Amperes at 105 volts	1·3	2·5	2·9	5·0	9·5	14·4	22·2	34·3	50·8	82·9	170	255	355	510	700

[1] See *Engineering*, xliv. 83, 1887; also *Electrical World*, ix. 4, 9 and 203; xiii. 309, 1889; xv. 114, 269 and 370, 1890; xvii. 130, 191. Also see Professor Crocker's book, entitled 'Practical Management of Dynamos and Motors,' and a series of papers by Professor Crocker in *Elec. Engineer* (N.Y.). 1891 and 1892.

Goolden's Mining Motor.—Mr. Atkinson has designed for Messrs. Goolden & Co. a mining motor of the simple bipolar

FIG. 343.—A.E.G. MOTOR.

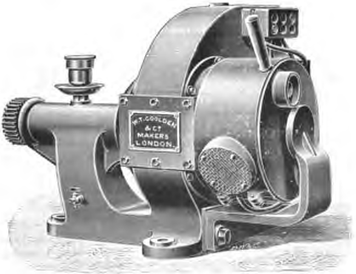


FIG. 344.—GOOLDEN ENCLOSED MINING MOTOR.

type, with special adaptations for use in coal-mines;[1] the moving parts being enclosed so that all possibility is removed of a spark at the brushes causing an explosion. As shown in Fig. 344, the commutator and brushes, which are of carbon, are completely boxed in.

Sayers' Mining Motor.—An entirely-enclosed mining motor, having fixed brushes and compensating armature on Sayers' design, has been introduced by Messrs. Mavor and Coulson. Fig. 345, which gives a section of this machine, shows the position of the auxiliary poles P_2, the use of which was described on p. 395. A 30-kilowatt motor, running at 700 revolutions per minute, weighs 3732 lbs. complete. The core-disks are deeply slotted with 4 main conductors and 3 commuting conductors in each of the 108 slots. The armature body is $9\frac{1}{2}$ inches long, and $17\frac{1}{2}$ in diameter.

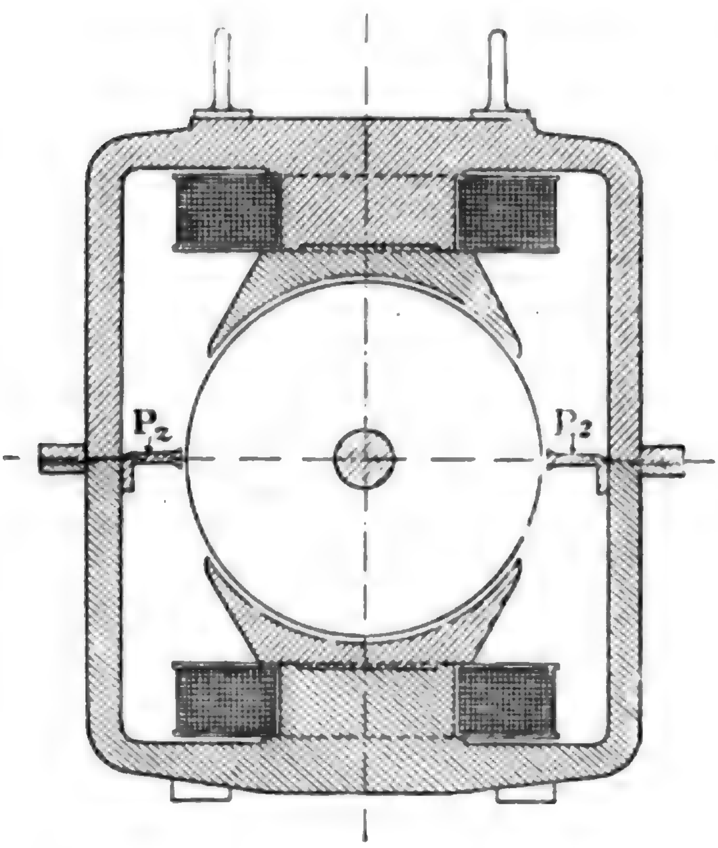


FIG. 345.—SAYERS' MINING MOTOR.

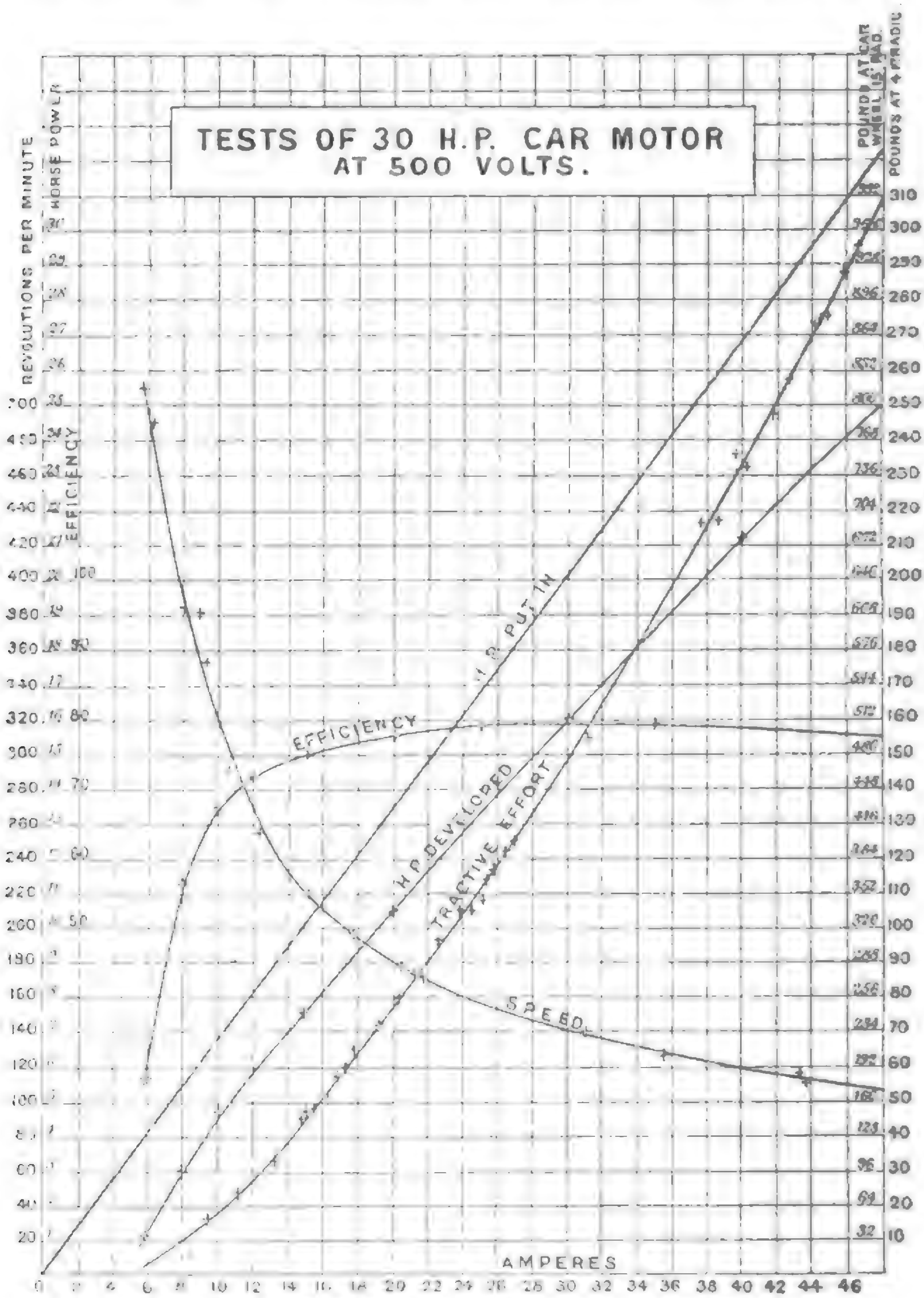
Electric Locomotive Motors.—Many motors have been designed for propelling tramcars and for electric railways; the points that inventors have chiefly considered being strong mechanical design of armature, slow speed with or without gearing, and construction that will resist deterioration by water, mud, dust, or overheating. Owing to the enormous rush of current just at starting, the armature must be capable of enduring the severest torque, and be practically fireproof as well as waterproof. For tramcar driving a single-reduction

[1] See the author's *Electricity in Mining*, p. 38, for descriptions of electric coal-cutters and other mining appliances.

gear has found general favour, but for heavy railroad work all gearings for speeding down have gradually fallen into disfavour, direct-driving slow-speed forms being more reliable. All this implies the employment of motors with relatively powerful field-magnets. This is not the place to enter on a detailed account of electric locomotion in general, or to describe any of the hundreds of electric tramways and railways now running. Suffice it to say that the lighter street-tramway systems have developed to an enormous extent in the United States, where alone more than 10,000 miles of electric street lines are at work, mostly with an overhead trolley-system of supplying current to the cars. The usual pressure is 500 volts. Generators suitable for such systems are described on p. 433. With respect to the motors, apart from the difficulties arising from damp, dirt and vibration, the main difficulty lies in designing the magnet,

FIG. 346.—MAGNETS FOR STREET-CAR MOTOR.

which must be both powerful and very compact. An early form used in the States resembled No. 32, Fig. 103, p. 163, but inverted.[1] More modern forms have four poles with very



TESTS OF 30 H.P. CAR MOTOR (WESTINGHOUSE CO.).

[1] See *The Electric Railway*, by O. T. Crosby and Louis Bell (New York,) 1892.

TEST OF A 30 H.P. WESTINGHOUSE STREET-CAR MOTOR.

Current	3½	10	20	30	40	50	60	70	80	90	94
Revs. of car axle ..	479	236	145	118	99	85	72	61	50	39	35
Torque (nett in lbs.-foot armature)	0	29	95	183	281	387	494	510	731	863	912
H.P. on brake	0	3·9	9·1	13·9	17·7	20·9	23·3	24·2	24·0	22·1	20·9
H.P. supplied electrically.	2·05	6·0	12·05	18·1	24·15	30·2	36·2	42·25	48·27	54·29	56·7
Electrical efficiency ..	98·5	96	91·5	86·8	81·3	76·2	70·5	63·0	54·5	45·0	40·5
Commercial efficiency	0	65	75·7	77	74	69·2	63·6	57·4	50·2	41·5	36·8
H.P. lost in copper ..	·028	·24	1·05	2·43	4·45	7·24	10·62	15·77	21·99	29·58	32·6
H.P. lost in iron, gearing, &c.	2·02	1·86	1·90	1·77	2·00	2·06	2·28	2·28	2·31	2·61	3·2
Ampere turns per pole	626½	1,790	3,580	5,370	7,160	8,950	10,990	12,530	14,320	16,110	16,825
Ampere turns in gap ..	500	1,600	2,900	3,400	4,060	4,500	4,950	5,200	5,500	5,750	5,850
$B_{\prime\prime}$ in gap	15,000	30,000	46,200	54,000	60,600	66,000	72,000	76,200	80,400	84,000	85,200
$B_{\prime\prime}$ in pole	14,400	28,800	44,400	51,600	60,200	63,000	69,000	72,600	76,800	79,200	81,600
$B_{\prime\prime}$ in armature	15,600	31,200	48,600	56,400	63,000	69,000	75,600	79,200	84,000	87,600	88,800
$B_{\prime\prime}$ in teeth	24,000	47,400	73,200	85,800	95,400	103,800	114,000	120,000	126,600	132,600	134,400

The dimensions of parts are as follows:—Armature, length, 15 inches; diameter, 11⅝ inches; diameter of bore, 12 1/16 inches; length of bore, 14 inches; core disks with 95 slots, 3/16 inch wide, 1 inch deep; 8 wires per slot, No. 11 B. and S. gauge. Total area of teeth, 280.5 sq. inch. Commutator, 8½-inch diameter, 2 11/16-inch face. Brushes, carbon, 2¾ inches long, 2 3/16 wide, 7/16 thick; sectional area, 1 sq. inch. Area of pole face, 75 sq. inches; section of pole piece, 73 sq. inches; area of yoke, 21 inches by 1½ inch. Lengths of magnetic paths: armature, 6 inches; teeth, 2 inches; gap, 7/16 inch; yoke, 25 inches. Sectional areas for magnetic lines: armatures, 134 sq. inches: teeth, 88·6 sq. inches; gap, 140 sq. inches; yoke (to carry half the flux), 73 sq. inches. Field winding, 179 turns per coil, 4 in series, No. 6 B. and S. gauge. Gear-ratio, 62 to 18.

short cores, with an arrangement for hinging the yoke-frame in two parts as shown in Fig. 346. The armatures of these motors are those represented in Fig. 217 in act of being wound. Fig. 347 gives other views of motor armature construction, and on p. 542 are given graphically the results of some tests of a 30 H.P. street-car motor of the Westinghouse Company when supplied at 500 volts. It will be seen that the efficiency is close to 80 per cent. In the Table on p. 543 are given

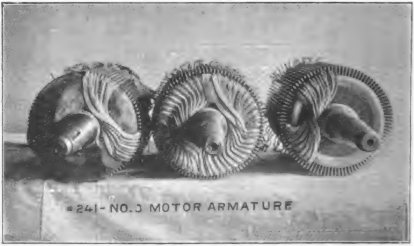


FIG. 347.—ARMATURES IN PROCESS OF CONSTRUCTION.

some data respecting another test of the same motor when run at 450 volts.

For tramway work Messrs. Mather and Platt make a standard type of single-reduction geared motor, as shown in Fig. 348, one-twelfth actual size. It is a Gramme armature, with single magnetic circuit steel magnets, suspended at or about their centre of gravity by a free suspension and carried on the other end by bearings on the axle. The armature is completely enclosed by casing, and the gear is of steel with teeth cut from the solid, the ratio varying from 3 : 1 to 4·5 : 1.

Heavy Railway Locomotive Motors.—In Plate XX. is given a sketch of the electric locomotive of the City and

South London subway railway, with two 50 H.P. motors designed by Dr. E. Hopkinson and constructed by Messrs. Mather and Platt. Each locomotive weighs about 10 tons, exerts 100 H.P., and can run over 25 miles per hour. They are series-wound, and run with magnets nearly saturated. The tractive effort with 100 amperes is 1180 lbs., with 226 amperes 3000 lbs. Fourteen of these locomotives are now running, and also two others by Siemens of a pattern in which the field-magnets are relatively more powerful, enabling the

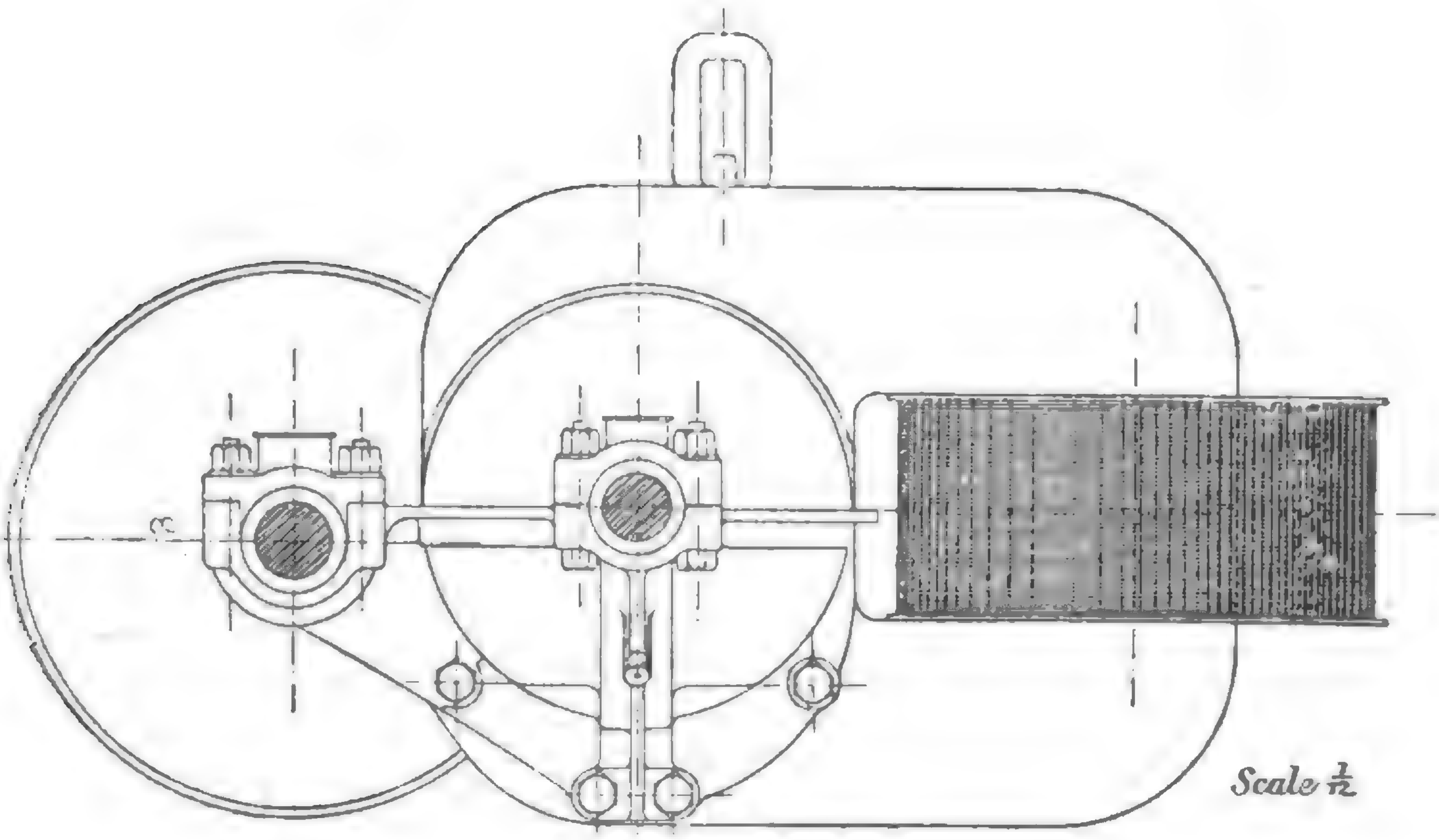


FIG. 348.—MATHER AND PLATT'S SINGLE-REDUCTION MOTOR.

armature to give the requisite torque with less current. All the fourteen locomotives supplied by Mather and Platt are still at work, having been in service since 1890, and having each run during that time on an average 120,000 miles. The principle of constructing the armature directly on the axle, which Dr. Hopkinson introduced for the first time on this line, has been followed in all cases where large powers at comparatively high speeds have been required, on account of its simplicity, efficiency and the small amount of wear and

tear. A smaller example is afforded by the 20 H.P. motor used in the Bessbrook Tramway, described by Dr. Hopkinson,[1] which ran at 1000 revolutions per minute, taking 100 amperes at 220 volts. It was series-wound, the resistance of armature being 0·112 ohm, and of magnet 0·113 ohm. The nett efficiency was over 90 per cent. This motor is reversed by simply reversing current in the armature.[2]

A still larger example of solid railway work is afforded by the Liverpool Overhead Railway,[3] the electrical machinery of which was built by the Electric Construction Corporation.

The largest electric locomotives yet made[4] are those designed by the General Electric Company, of Schenectady, for the Baltimore and Ohio Railroad. Each locomotive weighs 95 tons, and has on it four motors each of 400 H.P. They are operated at 600 volts, and exert their maximum pull of 47,500 lbs. when running at 15 miles per hour, the current then being 2700 amperes. The motors, of the 6-pole type, are grouped two in series. The generating station will contain four 10-pole 500 kilowatt direct-driven dynamos over-compounded from 600 to 700 volts.

Pulsating Motors.—The early type adopted by Page, Hjorth and others, with a reciprocating movement, has been revived in recent years for motors for the special purposes of operating hammers or drills. In 1879, Werner von Siemens[5] produced a mining drill in which a continuous current and an alternating current of slow period were combined to produce a reciprocating movement without a commutator. In 1880 Marcel Deprez[6] designed an electric hammer for forging, having a plunger of iron to be drawn up and down in a cylindrical coil wound in sections, into which the current was successively led by a commutator. Atkinson has lately designed a pulsating motor of remarkable novelty for mining drills.

[1] *Proc. Inst. Civil Engineers*, xci. part i., 1887–8.

[2] For a full description, see *Railway World*, August 1893.

[3] See paper by J. H. Greathead, before *Iron and Steel Institute, Liverpool*, Sept. 20, 1892. See also *Elec. Review*, xxxii. 151.

[4] See *Engineering*, July 19, 1895.

[5] D.R. Patent, No. 9469 of 1879 (see vol. ii. 389 of Siemens' *Arbeiten*).

[6] *La Lumière Électrique*, ix. 44, 1883.

CHAPTER XXII.

THE PRINCIPLES OF ALTERNATE CURRENTS.

In alternate-current working, the current is rapidly reversed, rising and falling in a succession of pulses or waves. Electricity is in fact oscillating backwards and forwards through the line with enormous rapidity, under the influence of a rapidly-reversing electromotive-force. The adjectives *alternate, oscillatory, periodic undulatory*, and *harmonic* have all been used to describe such currents. The author would prefer the term *wave-currents* as being both shorter and more apposite. The properties of alternate currents differ somewhat from those of continuous currents. They are affected not only by the resistance of the circuit but also by the magnetic reaction commonly called self-induction or inductance; the inductance of the circuit having a choking effect on the alternating currents, diminishing the amplitude of the waves, retarding their phase and smoothing down their ripples. They are also affected by the capacity or condenser action of the circuit. If a condenser is placed in an electric circuit, it completely blocks the flow for continuous currents; but alternating currents can oscillate into and out of its electrodes as though the condenser allowed them to pass through. On account of these peculiarities, some preliminary account of alternating currents is needed.

If a coil of suitable form is placed, as in Fig. 350, between the poles of a magnet, and spun around a longitudinal axis, it will have currents generated in it which at each semi-revolution die away and then reverse. In the figure the coil of wire is supposed to be so spun that the upper portion comes towards the observer. In that case, the arrows show the direction of the induced currents delivered to the circuit through the agency of two contact rings (or slip-rings) connected

respectively to the ends of the coil. In the position shown, the current will be delivered to the left-hand ring, and returns from the circuit to the right-hand ring; but half a turn later it will be flowing to the right-hand ring and returning from the circuit back to the left-hand ring. Fig. 350 is, in fact, a primitive form of alternator, generating a simple periodically reversed or alternating current; and is, in fact, the kind of alternator known as a "magneto-ringer," used for bell service in telephone sets. The simple revolving coil, by cutting the lines of the magnetic field, sets up periodic electromotive-forces, which change at every half-turn, giving rise to alternate currents. In each whole revolution there will be an electromotive-force which rises to a maximum and then dies away, followed immediately

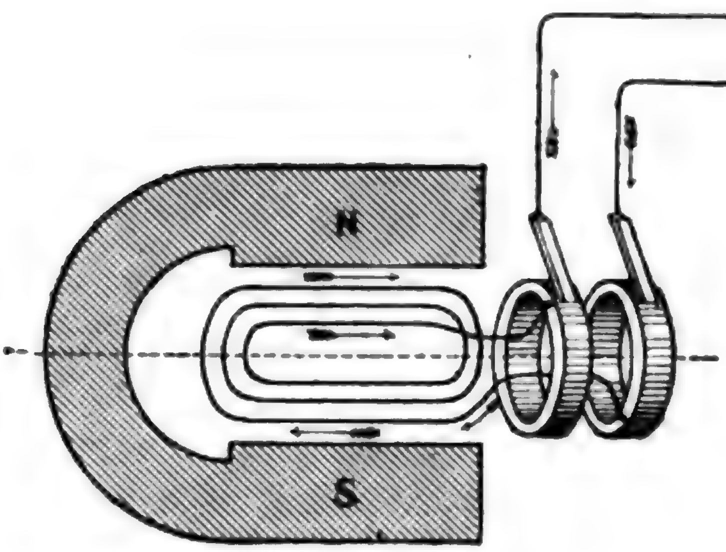


FIG. 350.

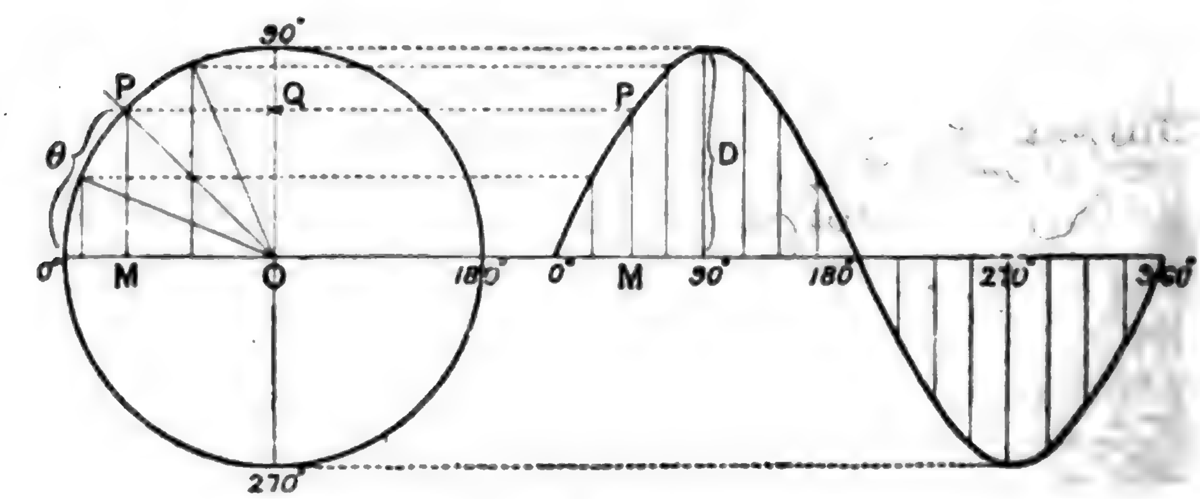


FIG. 351.

by a reversed electromotive-force, which also grows to a maximum and then dies away. The wave-form depicted in Fig. 351 serves to illustrate this. The heights of the

curve above the horizontal line represent the momentary values of the electromotive-forces; the depths below, in the second half of the curve, represent the inverse electromotive-forces that succeed them. Each such complete set of operations is called a *period*, and the number of periods accomplished in a second is called the *frequency* or *periodicity* of the alternations, and is symbolised by the letter n. In 2-pole machines n is the same as the number of revolutions per second; but in multipolar machines n is greater, in proportion to the number of pairs of poles. Thus, in an 8-pole field with four north poles and four south poles around a centre there will be produced four complete periods in one revolution. If the machine revolves 15 times a second (or 900 times a minute) there will be 60 periods a second, or the periodicity will be 60. By revolving in a uniform field the electromotive forces set up are proportional to the sine of the angle through which the coil has turned from the position in which it lay across the field. If in this position the flux of magnetic lines through it were N, and the number of spirals in the coil that enclose the N lines be called S, then, as was shown on p. 173, the value of the induced electromotive-force at any time t when the coil has turned[1] through angle $\theta = 2\pi n t$ will be

$$E_\theta = 2\pi n \mathrm{S}\,\mathrm{N} \sin\theta \div 10^8,$$

or, writing D for $2\pi n \mathrm{S}\,\mathrm{N} / 10^8$, we have

$$E_\theta = \mathrm{D} \sin\theta.$$

In actual machines the magnetic fields are not uniform, nor the coils simple loops, so the periodic rise and fall of the electromotive-forces will not necessarily follow a simple sine law. The form of the impressed waves will depend on the shape

[1] If n is the number of revolutions per second, $2\pi n$ will be the total angle (in radians) turned through in one second. Hence, the angle turned through (which we call θ), in any short time t will be equal to t times $2\pi n$. For example, if $n = 15$, $2\pi n = 94{\cdot}2$ radians per second, and during, say one-eightieth of 1 second, the angle passed over will be $1{\cdot}18$ radians, or about 67°.

of the polar faces, and on the form and breadth of the coils. But in most cases we are sufficiently justified in assuming that the impressed electromotive-force follows a sine law, so that the value at any instant may be expressed in the above form, where D is the maximum value or *amplitude* attained by E, and θ an angle of *phase* upon an imaginary circle of reference. As diagrams of lines revolving around a centre are much used in explaining alternate-current actions, the following explanation[1] should be most carefully followed. Consider a point P revolving clockwise round a circle (Fig. 351). If the radius of this circle be taken as unity, P M will be the sine of the angle θ, as measured from 0°. Let the circle be divided into any number of equal angles, and let the sines be drawn similarly for each. Then let these sines be plotted out at equal distances apart along the horizontal line, as in Fig 351, giving us the sine curve.

Now, the use that we make of this diagram is this. We know that as time goes on, the value of the electromotive-force is changing from instant to instant. To find its value at any particular instant, we *treat time as if it were an ever-increasing angle;* we take the number of seconds or the fraction of a second, that has elapsed since a certain instant t_0 (when the electromotive-force was zero), and multiply it by $2\pi n$, then considering this as an angle expressed in radians, the sine of this angle multiplied by D gives us in volts the electromotive-force for the particular instant. It will therefore be seen that the point P, in revolving uniformly round the circle in Fig. 351, represents the lapse of time. If we consider it revolving at such a speed that it passes through $2\pi n$ radians in one second, then the perpendicular P M represents (to some scale or other) the electromotive-force at any particular instant. Now taking the horizontal line $0° - 360°$ to represent time (to some convenient scale), it is evident that after the lapse of the time measured by the distance from 0° to M the electromotive-force has the value M P; and in the same way, at any other instant, the electromotive-force is repre-

[1] Those who are not familiar with the problems of simple-harmonic motions should consult some modern treatise of theoretical mechanics on the subject.

sented by the perpendicular drawn from that point in the line which represents the instant to the sine curve shown in the figure. In Fig. 351, one revolution of P around the circle of reference corresponds to one complete alternation or cycle of changes. The value of the electromotive-force (which varies between + D and − D as its maximum values) may be represented at any moment either by the sine P M or by projecting P on to the vertical diameter, giving O Q. As P revolves, the point Q will oscillate along the diameter. We may, therefore, without drawing our sine curve at all, merely consider a line O P (drawn to some scale to represent D) as revolving round O, and take its projection O Q at any instant as the electromotive-force. Such a diagram is known as a *clock diagram*.

The currents which result from these periodic or alternating electromotive-forces are also periodic and alternating; they increase to a maximum, then die away and reverse in direction, increase, die away, and then reverse back again. If the electromotive-force completes 100 such cycles or reversals in a second, so also will the current.

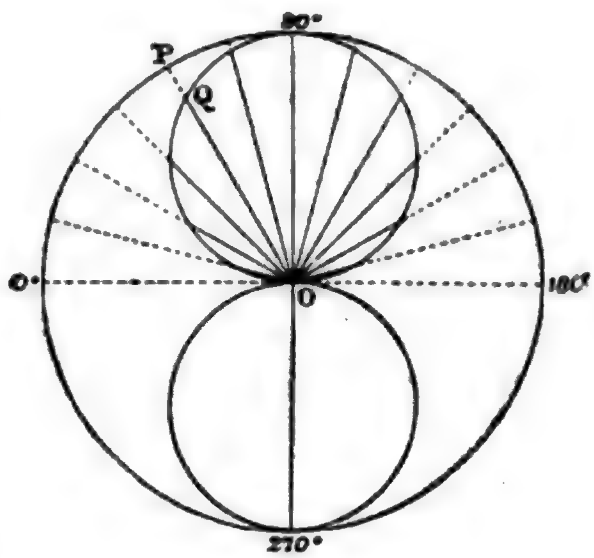


FIG. 352.

There is yet another way of representing periodic variations of this kind—namely, by a diagram akin to that used by Zeuner for valve-gears. Let the outer circle (Fig. 352) be as before a circle of reference around which P revolves. Upon each of the vertical radii describe a circle. Then the lengths such as O Q, cut off from the radii, represent the corresponding values of the sine of the angle. If a card with a narrow slit cut radially in it were made to revolve over this figure, the intersection with the two inner circles would show the varying electromotive-forces in various positions.

The reader who desires to pursue the graphic study of

these matters further should consult the excellent treatise of Prof. Fleming,[1] or that of Mr. Blakesley,[2] and sundry papers by Mr. Kapp.[3] Bedell and Crehore,[4] devote a whole chapter to the subject. In the case of real machines in which the magnetic fields are not uniform, nor the coils simple loops, the periodic rise and fall of the electromotive-forces will not necessarily follow a simple sine law. The form of the impressed waves will depend on the shape of the polar faces, and on the form and breadth of the coils. Consider the case of a machine in which the field-magnets consist of a double crown of opposing poles (as in the machines of Siemens, Ferranti, Mordey, &c.). If the armature coils and magnet cores are both of circular form, and equal in diameter, as the coils approach the polar ends of the cores they will, it is true, gradually enter the field, and the number of lines cut by the coil during equal displacements will gradually increase and become a maximum when the axis of coil and core coincides, and from that point it will again decrease, almost in a sine law; the greatest rate of cutting being when the edge of the coil is opposite the centre of the core; but if coil and core be rectangular in outline, the greatest rate of cutting in each wire will be when one edge of the coil is passing the edge of the pole. In this case the sine law cannot be true for the electromotive-force. In order to test whether in any given dynamo the rise and fall of electromotive-force and of current in the armature coils conforms to the law of sines, experiments are necessary. Joubert, in order to measure the currents of a Siemens dynamo, employed an electrometer method, and took off the current at any desired phase by a special commutator, and found an approximate curve of sines.[5] Another

[1] Fleming, *The Alternate Current Transformer*, London, 1889. Also a paper on Polar Diagrams, *Electrician*, xxxv. 43.

[2] Blakesley, *Alternating Currents of Electricity*, London, 1889.

[3] Kapp on "Alternate Current Machinery," *Proc. Inst. Civil Engineers*, 1889, pt. iii.

[4] Bedell and Crehore, *Alternating Currents*, London, 1893.

[5] For references as to modern varieties of this method see p. 712. During recent years many experimental methods have been given for determining the shape of the curve followed by the variations of alternating electromotive-forces and currents. The reader should consult the methods pursued by Ryan,

method, applicable also to direct-current machines, due to Mr. Mordey, is described.

In Fig. 353 are given four curves for a half-period. Of these one is a sine-curve, the other three form actual alternators, showing how nearly they agree with a true sine-curve. The one which agrees most nearly is that of the Mordey alternator, which lies just within the sine-curve nearly throughout its whole extent. The curve is usually more peaked in machines which have the coils sunk between iron teeth and have much armature-reaction. In the Niagara generators they are, on the contrary, rather flatter-topped and broader than true sine-curves. We are then sufficiently justified in assuming that the impressed electromotive-force follows a sine law.

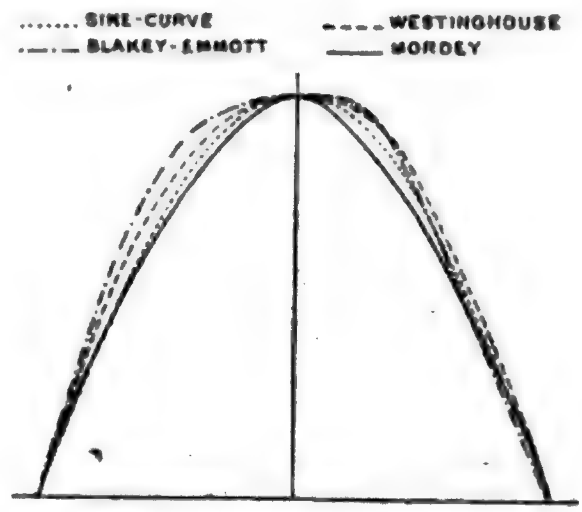


FIG. 353.—CURVES OF ALTERNATORS.

"Virtual" Volts and Amperes.—Alternate-current voltmeters and alternate-current amperemeters do not measure

Amer. Inst. Elec. Engineers, 1888 and 1889; also *Electrician*, xxiv. 263, 1890; Bedell, Miller and Wagner, *Amer. Inst. Elec. Engineers*, x. p. 500; Fleming, *Electrician*, xxxiv. 460, 507, 1895; L. Duncan, *ibid.* 617; Hicks, *ibid.* 698. Fleming's method is applicable to determine the form of the current curve at any part of a circuit. See also a paper by Barr, Burnie and Rodgers, *Electrician*, xxxv. 719.

Some controversy arose in the columns of the *Electrician* and of the *Electrical World*, in the autumn of 1894, as to whether there was any advantage in alternators giving a sine-curve. Fleming has since found that certain transformers worked with a distinctly higher efficiency when operated by an alternator giving a peaked curve than when operated by one giving a nearly pure sine-curve for the electromotive-force. On the other hand, this form appears to be undesirable for motor-running. As a matter of fact, the form of the current curve depends, not only on the construction of the alternator, but also upon the modifying influences of capacity and self-induction in the circuit. The presence, in the circuit, of transformers with iron cores and of motors will modify the curve; and the modification will specially depend on the degree of saturation to which the iron cores are carried at each cycle. A paper by Barr, Beeton and Taylor, in the *Electrician*, xxxv. 257, 286, is of great importance.

the arithmetical average values of the volts and of the amperes. They measure what are called *virtual volts* and *virtual amperes.* In a Cardew voltmeter the heating of the wire depends on the square of the current. In an electro-dynamometer the torque depends at every instant on the product of the currents in the fixed and movable parts; therefore, when used as an amperemeter, depends on the square of the current. The attraction (or repulsion) in electrostatic voltmeters is proportional to the square of the volts. The readings which these instruments give us, if first calibrated by using steady currents, are not true means, but are the square roots of the means of the squares. Now the mean[1] of the squares of the sine (taken over either one quadrant or a whole circle) is ½; hence the square-root-of-mean-square value of the sine functions is got by multiplying their maximum value by $1 \div \sqrt{2}$, or by 0·707. But[2] the arithmetical mean of the values of the sine is 0·637. Hence an alternating current, if it obey the sine law, will produce a heating effect greater than that of a steady current of the same average strength, by the ratio of 0·707 to 0·637; *i.e.* about 1·1 times greater. If a Cardew voltmeter is placed on an alternating circuit in which the volts are oscillating between maxima of + 100 and − 100 volts, it will read 70·7 volts, though the arithmetical mean is really only 63·7; and 70·7 steady volts would be required to produce an equal reading.

The term *virtual*[3] has been used to denote these square-

[1] See proof, p. 558.

[2] Or more strictly

$$\frac{1}{\theta}\int_0^\theta \sin\theta\, d\theta = \frac{1-\cos\theta}{\theta},$$

whence, if $\theta = \frac{\pi}{2}$, the average is $\frac{2}{\pi}$.

[3] I adhere to the term *virtual*, which was in use before the term *efficace* which was recommended in 1889 by the Paris Congress to denote the square-root-of-mean-square value. I adhere to it mainly because the adjective *effective* is required in its usual meaning in kinematics to represent the resolved part of a force which acts obliquely to the line of motion, the effective force being the whole force multiplied by the cosine of the angle at which it acts with respect to the direction of motion.

root-of-mean-square values. If an alternate-current amperemeter reads 100 amperes, that means that the current really rises to + 141·4 amperes and then reverses to − 141·4 amperes; but the heating effect and the amount of power delivered are the same as if the current were 100 continuous amperes, and therefore such a current would be described as 100 virtual amperes.

It may be remarked in passing that the virtual electromotive-force of a dynamo wound for alternate currents will therefore be 1·1 times higher (compare p. 589) than that of the same dynamo wound as a continuous-current dynamo of the same current-carrying capacity; or will be 2·2 times higher if, while the same wire is used, the alternator is not re-entrant, but forms a single circuit.

The distinction between virtual and maximum values is important since certain effects—for example the tendency to pierce insulation with a spark—depend on maximum, not on virtual values. For example, if an electrostatic voltmeter reads 10,000 volts; the maximum value (supposing the law of variation a sine law) will be 14,142 volts. If the curve is more peaked than that of the sine curve, the maximum will be higher.

Use of Clock Diagrams.—In these polar diagrams the amperes or the volts that are undergoing periodic cycles of change are represented by the projection on some given line (in this book, the projection on a vertical line is taken) of a line supposed to revolve about a centre. Such diagrams are of so frequent use in the study of alternating currents that a few further points about them are given.

Differences of *phase* are in the clock diagram represented by differences of angular position. For example, if two revolving pointers O V and O C (Fig. 354) are going round at the same rate, but always one a little behind the other, they will not come to their respective maximum at the same instant. Projecting them upon the vertical line we see that at the moment when O V has revolved so far that the angle of position is θ, its projection will have the value O v; while the other pointer, which lags behind by an amount measured

by the angle ϕ (=V O C), has for its value as projected, the length O c. When O v gets to its maximum (that is when V arrives at the top), O c will still be behindhand. The values of the two projections are O v = O V . sin θ; and O c = O C . sin $(\theta - \phi)$. The angle ϕ is the *difference of phase.*

To add together two different alternating quantities—for instance two electromotive-forces—that have the same period, it is not sufficient simply to add their numerical values. For instance, if there are two coils in series in a circuit in one of which there is being induced an alternating electromotive-force of 40 volts, and in the other an alternating electromotive-force of 30 volts (both having, let us say, the same frequency of 100 periods per second), the total electromotive-

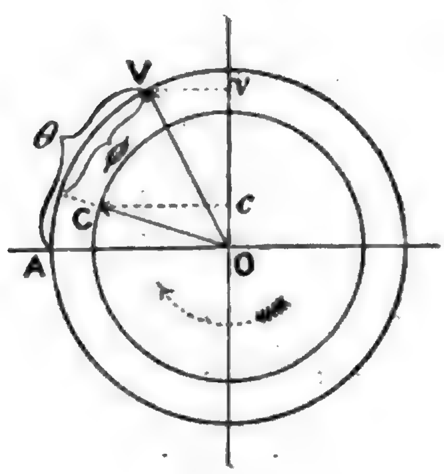


FIG. 354.

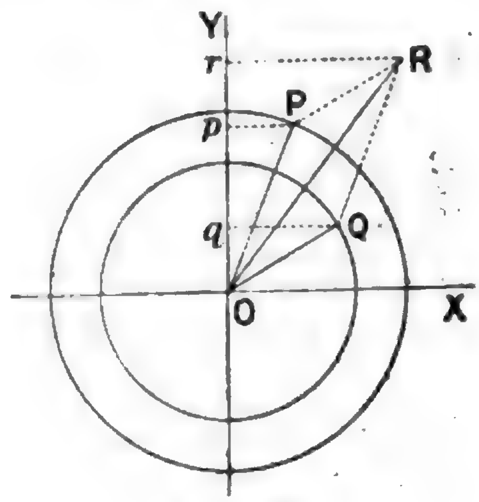


FIG. 355.

force will not be 70 volts unless the two electromotive-forces happen to be exactly "in phase." If there is any difference of phase between them the resultant will be less than 70 because they do not come to their maxima at the same time. To ascertain the value they have when added together we must apply the principle of summation of vectors with which every engineer is familiar in the ordinary compounding of forces by constructing a parallelogram.

Let O P and O Q represent two electromotive-forces, of the same period, but with a phase difference between them of P O Q which we may call angle ϕ. Completing the parallelogram by drawing P R equal and parallel to O Q, we get the resultant O R which represents the relative magnitude and

phase of the resultant revolving vector. The projection O r of this line will always be equal to the sum of the projections O p and O q of the two components. Now, by ordinary geometry we have $OR = \sqrt{OP^2 + OQ^2 + 2\,PQ\cos\phi}$. This is obviously a maximum when $\phi =$ zero. For instance if in the above example $OP = 40$, $OQ = 30$, and $\phi = 37°$. it will be found that the resultant O R is 66·6.

If the two components are at right angles to one another, on the diagram one will have its maximum at the instant when the other has its minimum. They are then said to be *in quadrature*, or as some electricians say, in *quarter-phase.* If they are equal in themselves the resultant will be greater than them in the proportion $\sqrt{2}$ to 1. For example, the resultant of two alternating electromotive-forces of equal period, of 100 (virtual) volts each, that are in quadrature, is 141·4 (virtual) volts.

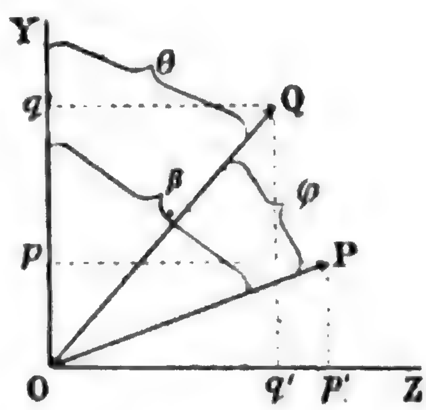


FIG. 356.

Products of Periodic Functions.—Suppose we have two periodic functions—say two currents, or a current and an electromotive-force — both varying with the same periodicity, but having different amplitudes and a difference of phase between them. Let one be called $p = OP \sin\theta$; the other $q = OQ \sin\beta$; where O P and O Q are their respective maximum values (as in Fig. 356), and ϕ the angle of phase-difference between them equal to $\theta - \beta$. Now, suppose we want to find the mean value of the product pq. This product will itself vary, but not as a sine function, and therefore is incapable of being represented as a line revolving. It will at certain instants—four times in each cycle—have zero values, for p comes twice to zero, and q comes also twice to zero. It will also have negative values when either p or q is negative. Its mean value will be the mean of all the values of the product during one complete cycle.

At the instant shown the product will be $pq = OP \,.\, OQ \cos\theta \,.\, \cos\beta$. A quarter-period later the two lines O P and

O Q will stand to the axis $-$ O Y in the same relation as they now stand to the axis O X, and the product (being positive) will then be

$$p' q' = \text{O P . O Q} \sin\theta \,.\, \sin\beta.$$

Taking the mean of these two values, we have

$$\begin{aligned} \frac{p\,q + p'\,q'}{2} &= \tfrac{1}{2}\,\text{O P . O Q} (\cos\theta \,.\, \cos\beta + \sin\theta \,.\, \sin\beta) \\ &= \tfrac{1}{2}\,\text{O P . O Q} \cos(\theta - \beta) \\ &= \tfrac{1}{2}\,\text{O P . O Q} \cos\phi. \end{aligned}$$

Now this is obviously independent of the actual position of θ or of β; that is to say, for every position the mean of the value between that position and the position at right angles is the same all the way round. Hence this value is the required true mean value of the product.

We shall make use of this theorem later.

A geometrical construction to illustrate the above is given in Fig. 357. Let O P and O Q represent the maximum values of two periodic functions as having phase-difference the angle ϕ or P O Q. Turn either of them (in this case O P) through a right angle so that it occupies the position O S, then complete the parallelogram O Q T S, and draw the triangle O Q S. The area of the parallelogram is equal to O P . O Q $\cos\phi$, and the area of the triangle is equal to $\frac{1}{2}$ O P . O Q $\cos\phi$, and therefore represents the mean product.

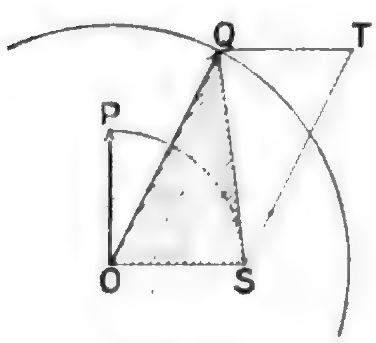


FIG. 357.

A further deduction is of use. Suppose p and q to be identical; we shall then obtain the mean value of the square of the periodic function by writing O Q = O P and $\phi = 0$; so that $\cos\phi = 1$. Then we get,

$$\text{mean value of } p^2 = \tfrac{1}{2}\,\text{O P}^2.$$

In other words, the mean value of the square of the sine is $\frac{1}{2}$.

Lag and Lead.—Alternating currents do not always keep in step with the alternating volts impressed upon the circuit. If there is inductance in the circuit the currents will *lag;* if

there is capacity in the circuit they will *lead* in phase. Fig. 358 illustrates the lag produced by inductance. The curve marked V represents the alternating volts; that marked C is the current curve. Distances measured from O along the horizontal line represent time. These curves are in fact similar to what would be obtained if curves were plotted from Fig. 354 in the same way as that plotted in Fig. 351, the points V and C being taken instead of the point P. The impulses of current, represented by the blacker line, occur a little *later* than those of the volts. But inductance has another effect of more importance than any retardation of phase; it produces reactions on the electromotive-force, choking the current down. While the current is increasing in strength the reactive effect of inductance tends to prevent it rising. To

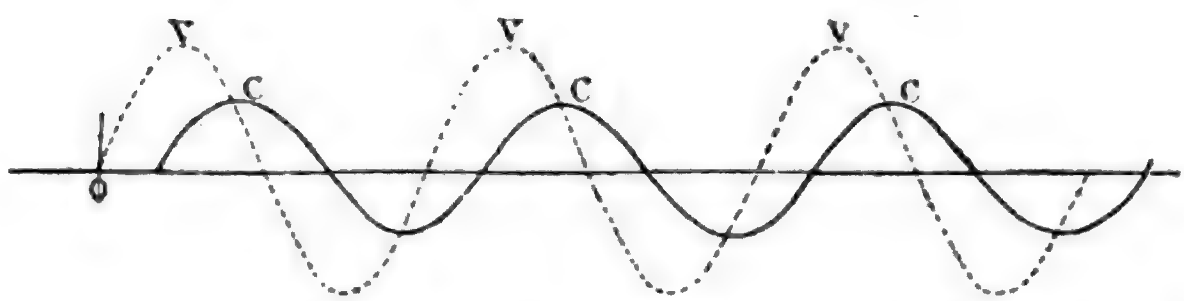


FIG. 358.—CURVE OF CURRENT LAGGING BEHIND CURVE OF VOLTS.

produce a current of 40 amperes in a resistance of 1½ ohms would require—for continuous currents—an E.M.F. of 60 volts. But an alternating voltage of 60 volts will not be enough if there is inductance in the circuit reacting against the voltage. The matter is complicated by the circumstance that the reactive impulses of electromotive-force are also out of step: they are, in fact, exactly a quarter period behind the current.

The Reaction of Inductance.—We have seen that every current is surrounded with a whirl of magnetic lines all along its length, the number depending on the permeability of the medium, and the distance between the going and returning wires. If the circuit consists of coils whose convolutions lie near one another, the whirls or loops of magnetic lines belonging to one part of the circuit will enclose another part of the circuit; so that whenever the current is growing or

dying away these loops of magnetic lines will be cutting across some other part of the circuit. In fact there will be *self-induction*, and the amount of cutting of magnetic lines that goes on when unit current is turned on or off (and which we may call the coefficient of self-induction, symbol L) will be proportional to the square of the number of spirals so reacting; or L is proportional to S^2. The presence of an iron core helps the magnetic field due to each convolution to thread itself around all the other convolutions. If the sectional area, length and permeability of the magnetic circuit in question are A, l and μ; then $L = 4\pi S^2 \mu \div 10^9 l$; where the factor 10^9 is introduced because the unit of induction, the *henry*, is chosen to correspond to the ohm and other units.

So then whenever in a circuit having an inductance L, the current is growing, there will be a self-induced electromotive-force reacting and tending to prevent the current growing; and the magnitude of this will be proportional both to L and to the rate of change of the current. If an alternate current of C (virtual) amperes is flowing with a frequency of n cycles per second through a circuit of inductance L, the reactive electromotive-force,[1] will be $2\pi n$ L C (virtual) volts. If, for example, $L = 0{\cdot}002$ henry, $n = 50$ periods per second, and $C = 40$ amperes, the reactive electromotive-force will be 25·1 volts. Now, if we wish to drive the 40 (virtual) amperes not only through the resistance of 1½ ohms but against this reaction, we shall require more than 60 volts. But we shall not require 60 + 25·1 volts, since the reaction is out of step with the current. Ohm's law is no longer adequate by itself as a guide. To find out what volts will be needed we must

[1] This is calculated as follows. By definition, L, the coefficient of self-induction, or inductance, represents the amount of self-enclosing of magnetic lines by the circuit when the current has unit value; when current has value C the number of lines enclosed is C times L. And, as the self-induced electromotive-force is proportional to the rate of change of this number, we may write $E = L \, . \, dC / dt$. Now C is assumed to be a sine function of the time having instantaneous value $C_0 \sin 2\pi n t$; where C_0 is the maximum value of C. Differentiating this with respect to time we get $dC / dt = 2\pi n C_0 \cos 2\pi n t$. The "virtual" values of cosine and sine being equal we have for E the value $2\pi n$ L C, but differing in phase from the current by a ¼ period.

calculate, either by algebra, or by geometry; and for greater simplicity we will have recourse to geometry.

Geometrical Investigation of the Law of Alternate Currents.—Plot out (Fig. 359) the wave-form O A b d, to correspond to the volts necessary to drive the current through the resistance, if there were no inductance. The ordinate a A may be taken to scale as 60. This we may call the R C curve. Then plot out the curve marked $-p$ L C to represent the volts needed to balance the reaction of the inductance. Here p is written for $2 \pi n$. The ordinate at O is 25·1: and

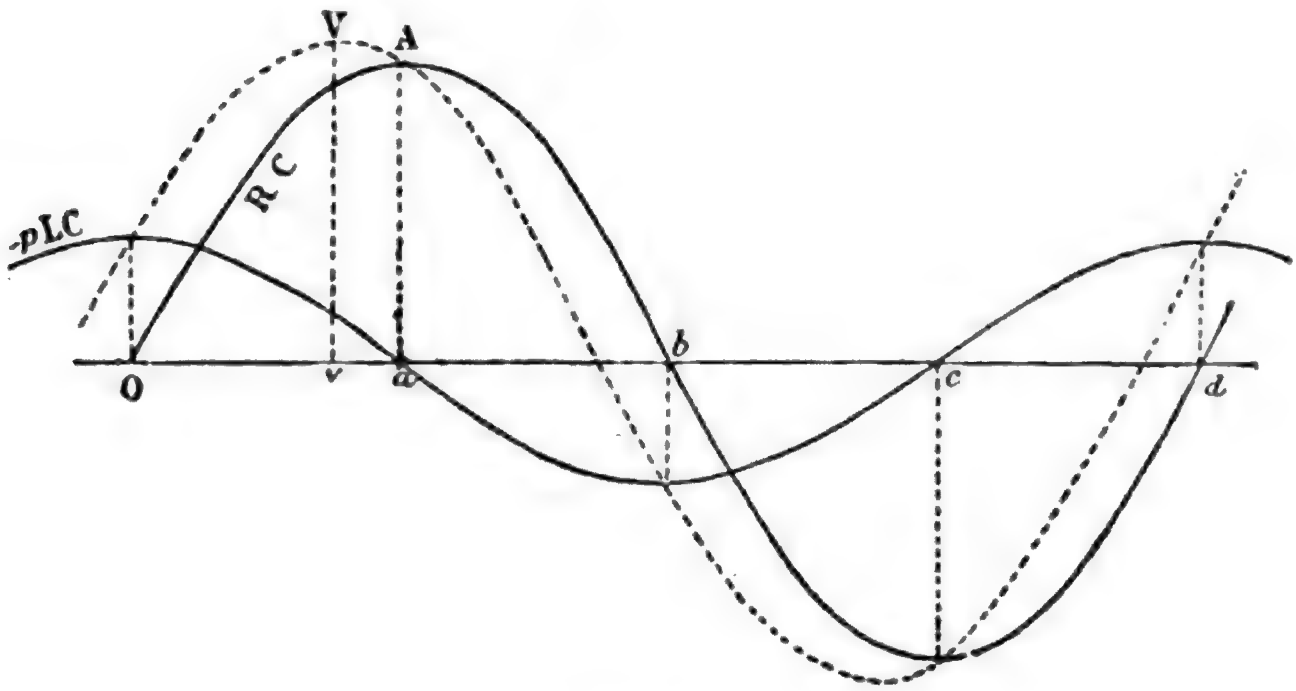


FIG. 359.

the curve is shifted back one-quarter of the period: for when the current is increasing at its greatest rate, as at O, the self-inductive action is greatest. Then compound these two curves by adding their ordinates, and we get the dotted curve, with its maximum at V. This is the curve of the volts that must be impressed on the circuit in order to produce the current. It will be seen that the current curve attains its maximum a little after the voltage curve. The current lags in phase behind the volts. If O d is the time of one complete period the length v a will represent the time that elapses between the maxima of volts and amperes. In Fig. 360 the same facts are represented in a revolving diagram of the same sort as

Fig. 354. The line O A represents the working volts R × C, whilst the line A D at right angles to O A represents the self-induced volts p L C. Compounding these as by the triangle of forces, we have as the impressed volts the line O D. The projections of these three lines on a vertical line while the diagram revolves around the centre O give the instantaneous values of the three quantities. The angle A O D, or ϕ, by which the current lags behind the impressed volts, is termed the *angle of lag.* However great the inductance or the frequency, angle ϕ can never be greater than 90°. If O A is 60 and A D is 25·1, O D will be 65 volts. In symbols, the impressed volts will have to be such that $E^2 = (R\ C)^2 + (p\,L\,C)^2$. This gives us the equation:

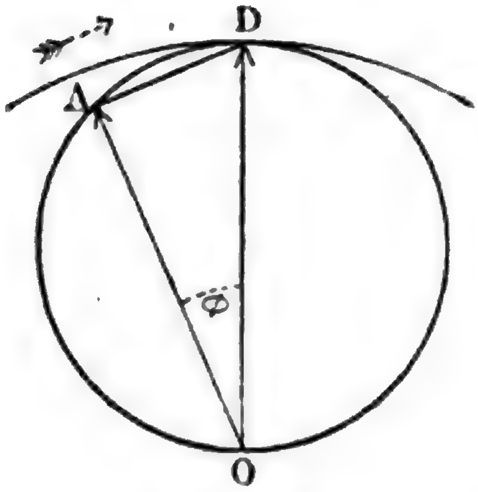


FIG. 360.

$$C = \frac{E}{\sqrt{R^2 + p^2 L^2}} \quad . \quad . \quad . \quad . \quad . \quad [I.]$$

The denominator which comes in here is commonly called [1] *the impedance.* Comparing this with the law for continuous currents, namely

$$C = \frac{E}{R},$$

we see that the effect of the inductance is to make the circuit act as if its resistance, instead of being R, was increased to $\sqrt{R^2 + p^2 L^2}$. In fact the alternate current is governed, not

[1] The term *impedance* strictly means the ratio of any impressed electro-motive-force to the current which it produces in a conductor (see Lodge's *Modern Views*, p. 398), of which the above is only one case. For steady currents the impedance is simply the resistance. For variable currents it may be made up of resistance, of inductance, and (if the circuit has electrostatic capacity), of permittance, in various proportions according to the *form* of the variation. For true periodic currents obeying the sine-law the impedance is the square root of the sum of the squares of resistance and inductance. For currents which vary more suddenly the impedance will depend more on self-induction and less on resistance.

by the resistance of the circuit, but by its impedance. The equation tells us the *magnitude* of the current, but not its *phase.*

In Figs. 361 and 362 the angle of lag is seen to be such that $\tan\phi = p\,\mathrm{L\,C} / \mathrm{R\,C}$ or $= p\,\mathrm{L} / \mathrm{R}$. The current is lagging as if the angle of reference were not θ but $\theta - \phi$, so that the

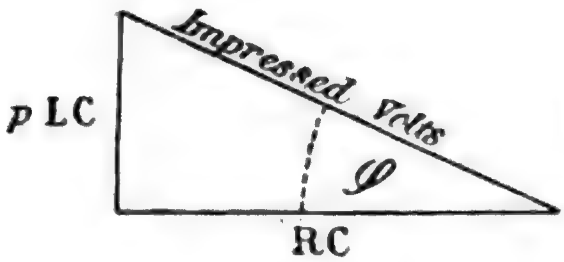


Fig. 361.

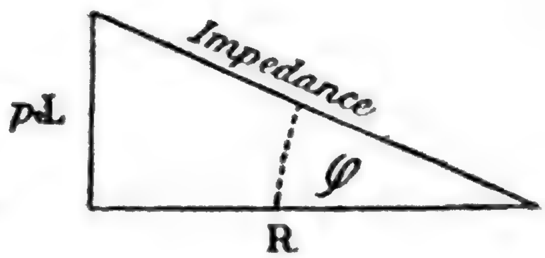


Fig. 362.

equation for C_t the instantaneous value of C at the moment when $\mathrm{E} = \mathrm{D}\sin\theta$, is

$$\frac{\mathrm{D}\sin(\theta - \phi)}{\sqrt{\mathrm{R}^2 + p^2\,\mathrm{L}^2}} \quad . \quad . \quad . \quad . \quad . \qquad [\mathrm{II.}]$$

This is Maxwell's law[1] for periodic currents as retarded by inductance. As amperemeters and voltmeters take no account of phase but give virtual values, the simpler form preceding is usually sufficient.

The relation between resistance and impedance is readily got from the triangle in Fig. 362; for clearly the angle ϕ is such that

$$\sin\phi = \frac{p\,\mathrm{L}}{\sqrt{\mathrm{R}^2 + p^2\,\mathrm{L}^2}},$$

$$\cos\phi = \frac{\mathrm{R}}{\sqrt{\mathrm{R}^2 + p^2\,\mathrm{L}^2}},$$

$$\tan\phi = \frac{p\,\mathrm{L}}{\mathrm{R}}.$$

If we prefer we may substitute for the impedance in the denominators of the preceding equations its value $\mathrm{R} / \cos\phi$.

The equations established above hold good, whether

[1] The analytical proof is given at the end of the present Chapter, p. 573.

maximum or virtual values are used. For example, we may write

$$\text{Maximum C} = \frac{\text{maximum E}}{\text{impedance}};$$

or

$$\text{Maximum C} = \frac{\text{maximum E}}{\text{resistance}} \times \cos\phi;$$

and

$$\text{Virtual C} = \frac{\text{virtual E}}{\text{impedance}};$$

or

$$\text{Virtual C} = \frac{\text{virtual E}}{\text{resistance}} \times \cos\phi.$$

The clock diagrams of revolving lines may be drawn either with maximum or virtual values.

Effect of Capacity.—When an electromotive-force is applied to a condenser the current plays in and out, charging the condenser in alternate directions. As the current runs in at one side and out at the other, the dielectric becomes charged, and tries to discharge itself by setting up an opposing electromotive-force. Its opposing potential rises just as its charge increases. A mechanical analogue is afforded by the bending of a spring, which as it is being bent exerts a back-force proportional to the amount of bending to which it has been subjected. When a periodic force is applied to a spring the elasticity of the spring tends to hasten the return movement. In like manner the electric elasticity of a condenser tends to hasten the return flow of the current.

The effect of capacity introduced into an alternate current circuit is to produce a *lead* in the phase of the current, since the reaction of a condenser, instead of tending to prolong the current, tends to drive it back. The student must clearly distinguish between the case of capacity in series with a circuit and the case of capacity in parallel with a branch of a circuit. What is said here refers to capacity in series, that is to say, the conductor of the circuit is actually cut and the ends joined to a condenser so that no current can flow except into and out of the condenser. If the capacity is in parallel

with a branch of a circuit, and we are considering what happens in that branch when there is a *given* alternating pressure at its ends, the capacity in parallel has no effect at all. If we are only given the pressure at some other part of the circuit, then the problem becomes more complex and involves the impedances of the circuit's various branches. Returning then to a simple circuit with a condenser in series, the smaller the capacity of the condenser the more does it react. The reactance is therefore written as $-1/pK$, being negative and

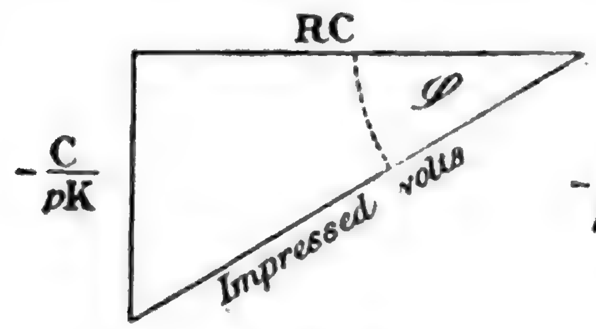


FIG. 363.

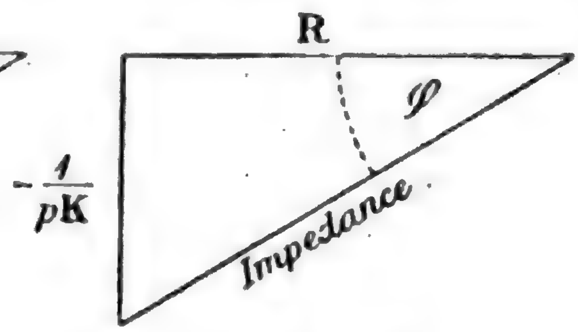


FIG. 364.

inversely proportional to K (the capacity in *farads*) and to p; and the angle ϕ will be such that $\tan\phi = -1/pKR$. The impedance will be $\sqrt{R^2 + 1/p^2K^2}$. Figs. 363 and 364 show the construction that is applicable in this case.

If both inductance and capacity are present, $\tan\phi = (pL - 1/pK)/R$; the reactance will be $pL - 1/pK$; and the impedance $\sqrt{R^2 + (pL - 1/pK)^2}$. This is illustrated by Fig. 365, in which the triangle for finding ϕ is drawn by setting out p L at right angles to R and then deducting from p L a part equal to $1/pK$.

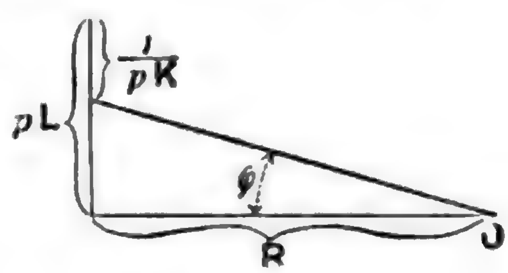


FIG. 365.

The same construction may be applied to a circuit containing several resistances, inductances and capacities.

Since capacity and inductance produce opposite effects, they can be used to neutralize one another. They exactly balance if $L = 1/p^2K$. In that case the circuit is non-inductive and the currents simply obey Ohm's law.

It will be seen that if in a circuit there is little resistance and much reactance, the current will depend almost exclusively on the reactance. For example, if p ($= 2\pi n$) were, say, 1000 and L = 10 henries, while R was only 1 ohm, the resistance part of the impedance would be negligible, and the law would become

$$C = \frac{E}{pL}.$$

The current would *lag* by almost 90°.

Self-induction coils with large inductance and small resistance are sometimes used to impede alternate currents, and are called *choking coils*, or impedance coils. This formula is wanted for calculating alternate-current electromagnets; for their apparent resistance is almost entirely due to inductance.

If the current were led into a condenser of small capacity (say $K = \frac{1}{10}$ microfarad, then $1/pK = 10{,}000$), the current running in and out of the condenser would be governed only by the capacity and frequency, and not by the resistance, and would have the value—

$$C = EpK,$$

and its phase will *lead* by almost exactly 90°.

A capacity acting laterally across the circuit, as when a condenser is placed across the two mains, has the effect of increasing the flow of current from the dynamo up to the points on the circuit which are connected to it, and therefore of raising the virtual potentials of those points, thereby affecting the voltage of the rest of the circuit. There is, for a given frequency, resistance and self-induction, one particular value of capacity which would enormously increase the current and voltage as by a sort of resonance. These various condenser effects have been considered by various writers. A very clear exposition of them, together with the phenomena observed on the Ferranti mains on the Deptford supply has been given by Fleming.[1]

Mean Power.—The power cannot be calculated by simply multiplying together the *volts* and the *amperes* as with continuous currents; for when there is any difference of phase

[1] *Journal Inst. Electr. Engineers*, xx. 362, 1891.

the *apparent watts* so calculated are always in excess of the *true watts.* We have seen on p. 558 that the mean product of two periodic functions is equal to half the product of their maximum values multiplied by the cosine of their phase difference: or

$$\text{Mean power (true watts)} = \tfrac{1}{2} E_{max} \times C_{max} \times \cos \phi,$$
$$= \frac{E_{max}}{\sqrt{2}} \times \frac{C_{max}}{\sqrt{2}} \times \cos \phi,$$
$$= E_{virt} \times C_{virt} \times \cos \phi.$$

One way of dealing with this is to consider the product $E_{virt} \times \cos \phi$ as the resolved part of the volts that is in phase with the current, and therefore equal to $C_{virt} \times R$. Hence we may write the mean power (true watts) as C^2_{virt} R. That is to say, if the resistance of the circuit is a plain non-inductive resistance (such as a load of lamps, or a water resistance) the true watts spent in it are found in the usual way by the C^2 R law. There is, however, another way of regarding the matter as follows.

Watt-less Current.—Whenever there is a great phase difference between volts and current (whether a lag due to self-induction or a lead due to capacity), the true watts are, as has already been pointed out, much less than the apparent value that would be obtained by merely multiplying together the virtual amperes and the virtual volts. For, as we have seen, this product must be further multiplied by the cosine of the angle of lag (or lead). Now there are two ways of looking at this matter, the product $E_{virt} \times C_{virt} \times \cos \phi$ may be regarded as either the product of the virtual amperes into the resolved part (or effective part) of the virtual volts, or it may be regarded as the product of the virtual volts into the resolved part of the virtual amperes. Just as any force may be resolved into two component forces at right angles to one another, so any alternating current may be resolved into two component alternating currents differing 90° in phase. Or C may be resolved into two parts, C $\cos \phi$ agreeing in phase with the volts, and C $\sin \phi$ in quadrature with the volts. These two resolved parts of the current may be termed the *working current* and the *watt-less current.* In Fig. 366, O E represents the effective part of the impressed electromotive-force O A. Of O E a part O I is

found, by dividing by R (p. 569), to represent the current C. Of this current the resolved part O W, in phase with O A, is the working current, and the part O U, which is in quadrature with O A, is the watt-less current. Whenever, for either cause, the angle of lag is great, the watt-less part of the current will be great also. For example, when transformers are left on open circuit, the current in the primary is nearly in quadrature (owing to self-induction) with the impressed volts, and, if it were not for hysteresis or eddy-currents in the iron cores, would be almost entirely watt-less.

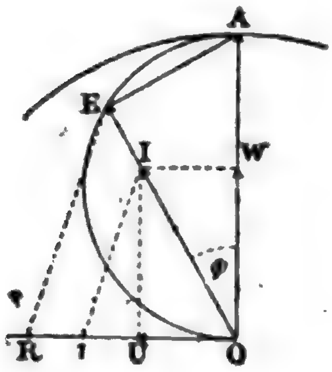


FIG. 366.

For example, if there is a current of 100 virtual amperes lagging 14° behind the impressed volts, this may be resolved into a working current of 97·03 virtual amperes, and a watt-less current of 24·2 virtual amperes.

Measurement of Alternate-current Power.—The considerations above show that this is a matter for care. If there is no phase-difference between volts and amperes, the apparent watts are the same as the true watts; and in that case amperemeter and voltmeter may be used.[1] But if there is a phase difference a suitable wattmeter must be used; the usual form being an electrodynamometer specially constructed so that the high-resistance circuit in it shall be non-inductive.

Numerical Example:—Let an impressed electromotive-force of 65 (virtual) volts, alternating with a frequency of 50 periods per second, act upon a circuit having resistance 1·5 ohms, and a coefficient of self-induction of 0·002 henry. Find the lag, the current, and the mean power.

To find the lag, we must find the inductance, $2\pi n L$, and divide this by the resistance; or

$$\tan\phi = 2\pi n L \div R = 2 \times 3{\cdot}1416 \times 50 \times 0{\cdot}002 \div 1{\cdot}5 = 0{\cdot}419.$$

Looking in a table of natural tangents, we find that ϕ will be 22° 44′; whence a table of natural cosines gives us $\cos\phi = 0{\cdot}9223$. Or,

[1] Those who are not familiar with this subject should consult the writings of Mr. Blakesley or those of Prof. Fleming. The three-dynamometer method of Blakesley, the three-voltmeter method of Ayrton, and analogous methods, are all of value. Fleming in *Journal Inst. Electr. Engineers*, xxi. 594, 1892, has after much experience given preference to a simple wattmeter method.

we might calculate cos ϕ directly as $R \div \sqrt{R^2 + 4\pi^2 n^2 L^2}$. Multiplying cos ϕ into the 65 volts, we get 59·95, say 60, as the effective virtual volts, and dividing by the resistance gives 40 virtual amperes as the current. The mean power is $65 \times 40 \times 0{\cdot}9223 = 2400$ watts.

Geometrically this is given in Fig. 367.

Let O A be 65 to any scale, the impressed (virtual) volts. Describe the circle of radius O A, and the semicircle O E A. Draw O B at right angles to O A. On O B set off O R on any convenient scale of resistance, O 1 being taken as 1 ohm. Using same scale, set off O S or R F at right angles, equal to the inductance $2\pi n L = 0{\cdot}628$. Join O F. R O F is the angle of lag. Draw E O at right angles to O F, cutting semicircle in E. E O A is also angle of lag, hence E O represents effective virtual volts; and A E the cross-electromotive-force of self-induction $2\pi n L C$. Join E R and from 1 draw 1 C parallel; C O will represent the current. As O B is O A turned through a right angle, the area of triangle B O C = ½ O A . O C . cos A O C = ½ mean power (see p. 558).

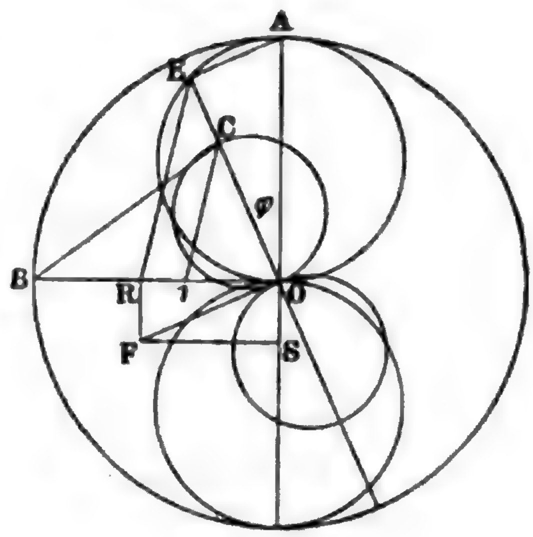
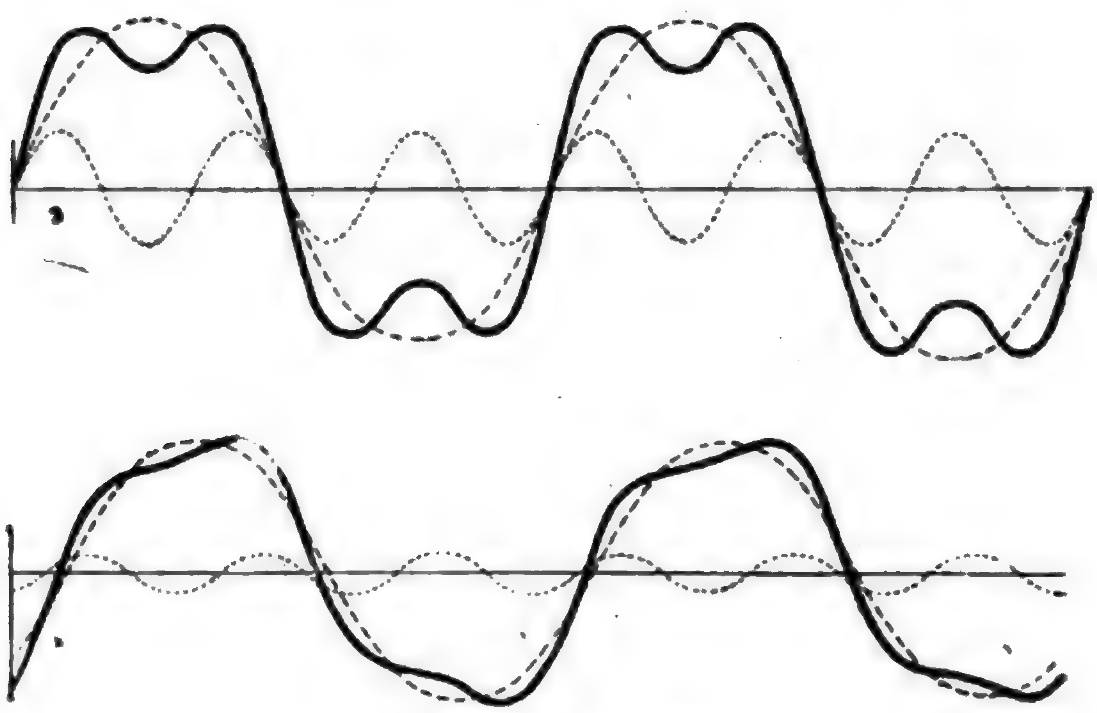


FIG. 367.

There are some reasons why it is desirable that the induction curves of alternators should follow the sine-form (but see p. 712 as to effect of wave-form on transformer efficiency). According to the well-known theorem of Fourier, every complex single-valued periodic function can be analysed down into a series of simple periodic functions differing in amplitude and phase, but all belonging to a harmonic series, having frequencies that are some exact multiple of a single fundamental frequency. Every complex wave-curve may be regarded as built up of sine-curves. For example, the curve shown in Fig. 368 may be looked upon as a compound of the two dotted sine-curves, one of a frequency three times that of the other. Now, if this complex curve represents the impressed electromotive-force of an alternator with curiously-shaped poles, what will the curve of effective electromotive-force (or of current) be when self-induction is present? The amplitude is cut down in proportion nearly to the frequency of the alternation. Hence the component ripple, which has three times the frequency, will be damped out nearly three times

as much as the fundamental wave.[1] In Fig. 369 are shown the two waves, as altered by a lag of 41° which cuts down the fundamental to 0·75, and the ripple to 0·35 of their respective amplitudes; the resultant wave being also shown. It is evident that self-induction tends to smooth out the ripples, including all parts of the wave that do not fit to the sine-form. Hence those alternators which give induction curves of true sine-form are less affected than others by self-induction in the circuit, regulate better, and have a higher plant-efficiency.

High Frequency Alternations.—Alternations of very high periodicity, going up to as many as 10,000 or 20,000 per second, have been studied by Spottiswoode,[2] and more recently by Tesla,[3] who



Figs. 368 and 369.

has obtained some very remarkable effects. One of his alternators was of the same type as Mordey's, having numerous polar projections on either side,[4] and another was of the inductor type. With these excessively high frequencies the currents flow almost exclusively along the surface layers of conductors, instead of flowing through their entire cross-section; even straight rods of copper offering a relatively enormous impedance.

[1] Much attention has been given to the analysis of alternate-current curves during recent years by Perry, Ryan, Fleming, Bedell and others.

[2] *Proc. Roy. Soc.*, xxiii. 455.

[3] *American Inst. Electrical Engineers*, May 1891. See *Electrical World*, xvi. 1891, and *The Electrician*, xxvi. 549, 1891.

[4] See *Electrical Engineer* (N.Y.), March 18, 1891.

Torque of Alternators.—A very singular result follows the presence of any lag in the current of an alternator. It was pointed out on p. 487, that where amperes flow with the volts, electric energy is being supplied by the machine, and power must be applied to drive it; but that when amperes flow against a counter electromotive-force, there electric energy is leaving the circuit and being turned into mechanical energy, helping to drive the machine. The one is the case of the generator, the other that of the motor. But now consider an alternator with the amperes lagging behind the volts, as indicated by the diagram of Fig. 370. It is clear that in consequence of this lag the amperes are sometimes flowing against the volts

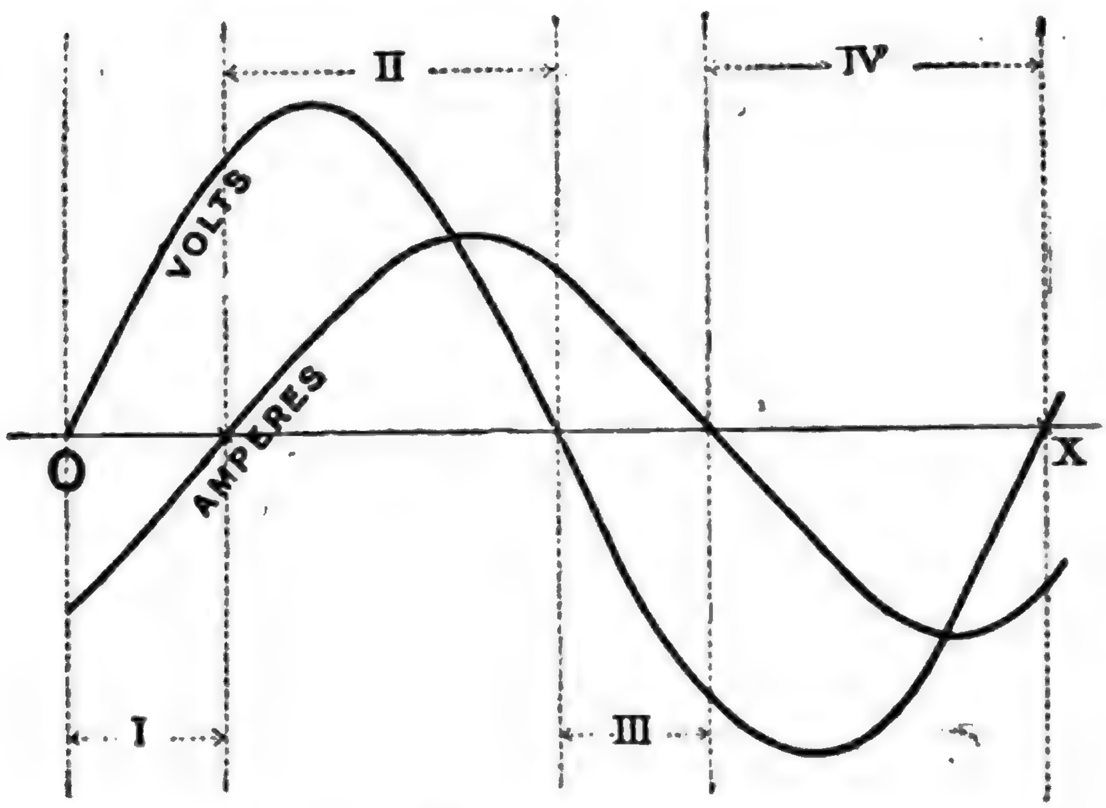


FIG. 370.—EFFECT OF LAG OF CURRENT.

instead of with them. In fact, we may divide each complete period such as OX into four parts, during two of which, namely II. and IV. in Fig. 370, the amperes and volts are alike in direction, either both positive, or else both negative; during the other two parts—namely I. and III.—the amperes and volts are opposed in direction because the volts have reversed in sign, but the lagging amperes have not yet changed. Now, during the partial periods II. and IV., when there is agreement in sign, the machine is in the condition of being a generator, and will require to be driven, the currents in the armature setting up a counter torque. But during the other partial periods I. and III., when there is opposition in sign, the machine is in the

condition of being a motor, and will tend to drive itself, the torque helping it on. The conductors are consequently subjected to a racking action, alternately resisting, being driven and then helping to drive twice in each period. It is clear that if there is little lag there will be little motor action, the partial periods I. and III. being brief; whereas if there is much lag the motor action will increase. If there is a lag of exactly a quarter of a period, the motor and generator actions will be equal. Similarly, if in consequence of capacity the current leads in phase, there will be motor action in partial periods. This subject may be considered in another way. The electromotive-forces change sign just as the conductors are passing (Fig. 371), from one magnetic field to another, where the lines run in an opposite direction. If the currents are in phase with the electromotive-forces, they will always tend to oppose the

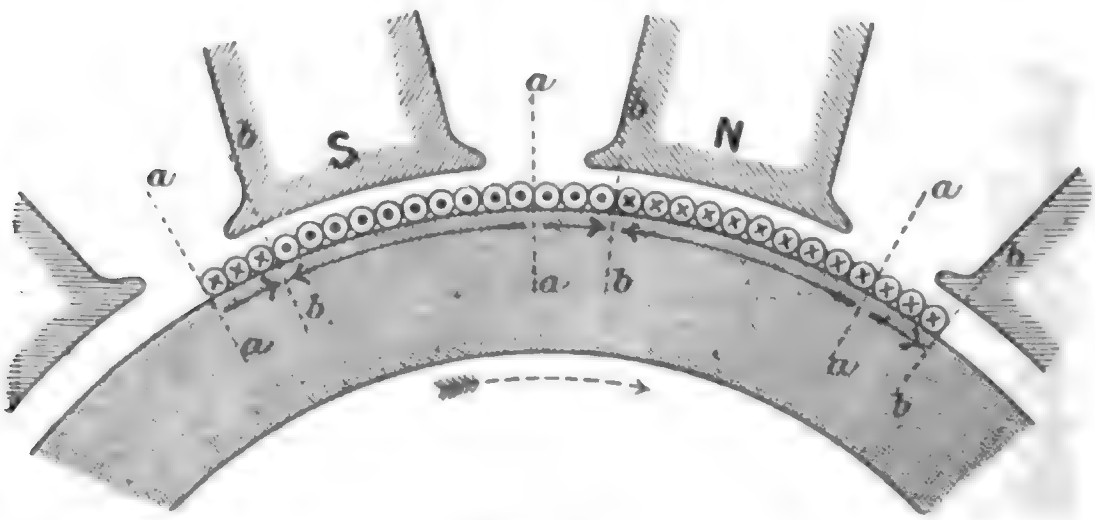


FIG. 371.

motion that generates them, and will reverse when the conductor passes into the reversed field as at *a*, *a*. But if the currents lag, the force exerted by the field will help on the motion of those conductors which have passed from one field to the other until such time as the currents have reversed at *b*, *b*.

It follows that when there is a difference of phase between volts and amperes, the mean power in a cycle is equal to the difference between the power which it gives out during the partial periods II. and IV., and the power which it receives back from the circuit during the partial periods I. and III. If the phase difference is less than 90° the machine acts on the whole as a generator. If it is more than 90° the machine acts as motor on the whole. If two alternators are coupled in

series, one to act as generator, the other as motor, the current will be nearly in phase with the electromotive-force in the one and almost exactly opposed to the electromotive-force in the other. This question is resumed in Chapter XXIV.

Analytical Treatment of Fundamental Equations of Alternating Currents.

Beginning with the case of a loop having S_2 turns, placed at such an angle θ (measured from the initial position as in Fig. 110, where it stands right across the field), we see that it no longer encloses the whole number of magnetic lines which are present in the magnetic circuit. When we omit all account of self-induction, we may write

$$\mathsf{N}_1 = S_2 \mathsf{N} \cos\theta, \qquad [\text{I.}]$$

where N_1 is the amount of flux actually enclosed by the loop in this position.

To get a complete account of the action we must now take into consideration the number of magnetic lines *induced by the circuit on itself.*[1]

If current C flow through a circuit whose coefficient of self-induction or inductance is L, the whole self-induction of the circuit will be equal to L times C; and the product L C will represent the

[1] Neumann's mathematical investigation of the effect of considering the self-induction of the circuit in relation to a periodic electromotive-force, was published in 1845, but self-inductive phenomena had previously been studied by Henry and by Faraday.

Other mathematical investigations of alternating electric currents have been given by Weber in his *Elektrodynamische Maasbestimmungen*, and by the following:—

Koosen, *Pogg. Ann.*, lxxxvii. 386, 1852.
Le Roux, *Ann. Chim. Phys.* [3], l. 463, 1857.
Clerk Maxwell, *Phil. Trans.*, 1865, p. 473.
F. Kohlrausch, *Pogg. Ann.*, cxlviii. 143, 1873.'
Jamin and Richard, *Ann. Chim. Phys.* [4], xvii., 276, 1869.
Joubert, *Ann. de l'École Normale Supérieure*, x, 1881; and *Journal de Physique*, s. ii. t. ii. p. 293, 1883.
Lord Rayleigh, *Phil. Mag.*, May 1886, p. 375.
Hopkinson, Lecture at Instit. Civil Engineers (on Electric Lighting), 1883.
,, *Jour. Soc. Telegr. Engineers*, xiii.
,, *Proc. Roy. Soc.*, Feb. 1887.

Abstracts of the most important of these will be found in Fleming's book on the *Alternate Current Transformer*.

total amount of enclosing of magnetic lines by the convolutions of the circuit.

But we know that if there is a current C in the circuit, we ought to write the equation in full—

$$\mathrm{N}_1 = \mathrm{S}_2\,\mathrm{N}\cos\theta + \mathrm{L}\,\mathrm{C}. \qquad [\text{II.}]$$

Now we know that any variation in N_1 will set up induced electromotive-force, and that at any moment the electromotive-force will have the value

$$\mathrm{E} = -\frac{d\,\mathrm{N}_1}{d\,t}; \qquad [\text{III.}]$$

where we use the negative sign to show that an increase in N_1 will produce an inverse or negative electromotive-force. Any change in N_1, from whatever source arising, will set up electromotive force. In the absence of armature reactions the only quantities whose variations contribute to the variations of N_1 are θ and C. The angle of position θ varies from 0 to 2π (radians); that is to say, from 0° right round to 360°, and then recurs; and its cosine therefore fluctuates between 1 and -1. The current C varies also from a certain maximum value $+\mathrm{C}_{max.}$ to an equal negative value $-\mathrm{C}_{max}$. We will neglect all the variations of the other quantities, not because these variations would not be instructive—for that would be quite untrue—but because of their lesser practical importance. Then we have

$$\mathrm{E}_t = -\frac{d\,\mathrm{N}}{d\,t} = -\frac{d(\mathrm{S}_2\,\mathrm{N}\cos\theta + \mathrm{L}\,\mathrm{C})}{d\,t}.$$

Now suppose that while the armature loop has turned through the angle θ, the time occupied—a small fraction of a second—is t. Also take T to represent the time taken for one revolution; so that if there were n revolutions[1] per second, T will be $1\,/\,n$ of a second. Then obviously θ will be the $\frac{t}{\mathrm{T}}$ part of a whole revolution, and as there are 2π radians in a circle, the angle expressed in radians will be

$$\theta = 2\pi\frac{t}{\mathrm{T}} = 2\pi n t = p t;$$

where p is written short for $2\pi n$, and called the *pulsation*.

[1] For multipolar machines the number of alternations is more numerous than the number of revolutions in proportion to the numbers of pairs of poles. The symbol n will in this case stand for alternations per second.

Inserting this value, and performing the differentiation, we get

$$E_t = 2\pi n S_2 N \,.\, \sin pt - L\frac{dC}{dt}; \qquad \text{[IV.]}$$

Consider this equation carefully. It shows us that when the dynamo is on open circuit, so that there is no current, then self-induction would not come in at all. The negative sign also indicates that that part of the electromotive-force which is due to the self-induction opposes the other part. Now write D for the group of symbols $2\pi n S_2 N$. Further, we know that that part of the electromotive-force which is effective in driving the current through the resistance may be calculated by simply applying Ohm's law. So if E_t, as found in formula [IV.], be the nett or effective electromotive-force at the time t, we may write $E_t = R C_t$; whence

$$R C_t = D \sin\theta - L\frac{dC}{dt}.$$

This is a differential equation of the form

$$ay + b\frac{dy}{dx} = \sin px.$$

(See Boole's *Differential Equations*, p. 38.)
The solution is

$$C_t = \frac{D\cos\phi \,.\, \sin(\theta - \phi)}{R} + c\,\epsilon^{-\frac{R}{L}t}; \qquad \text{[V.]}$$

where ϕ is called the retardation or angle of *lag*, and has the value such that

$$\tan\phi = \frac{2\pi n L}{R}.$$

In the second term of the expression on the right-hand side of the above equation, the symbol c is a constant of integration, and ϵ is used in its common mathematical sense to represent the number 2·7182, which is the basis of the Napierian (or hyperbolic) logarithms. This second term relates only to the irregularities during the first starting of the current, and dies out as the time t increases in value. The phenomenon of inductive rush, sometimes noticed when current is suddenly switched on or off, is of this nature. In general the exponential term may be omitted.

We have, therefore, got our equation for the current at time t as follows:—

$$C_t = \frac{D \cos \phi \cdot \sin (\theta - \phi)}{R}; \qquad [VI.]$$

which should be compared with the value D sin $\theta \div$ R that the current would have if there were no self-induction. We see by comparing the two expressions that our current still follows a sine-function, but it is the sine-function not of the angle θ, but of the angle $(\theta - \phi)$; that is to say, its waves *lag* behind those of the impressed electromotive-force. Also, the amplitude of the current is reduced, because everything is going on as if the amplitude of the impressed electromotive-force had been altered from D to D cos ϕ. Or, in other words, the effective electromotive-force is equal to the part of the impressed electromotive-force as resolved along the line of the lagging current. If we substitute for cos ϕ its value $R / \sqrt{R^2 + p^2 L^2}$, we reduce the equation to the form

$$C_t = \frac{D \sin (\theta - \phi)}{\sqrt{R^2 + p^2 L^2}}; \qquad [VII.]$$

which is what we deduced from geometrical considerations.

To establish the equations for the case of a circuit possessing capacity and resistance only, we may proceed very simply to calculate what impressed electromotive-force is needed both to drive the current through the resistance and to charge the condenser. Assume $C = C_0 \sin \theta$. Let the condenser of capacity K (farads) have a charge q at any instant, then its potential will be q / K, and the corresponding electromotive-force needed at that instant to drive the current will be

$$RC + \frac{q}{K} = E.$$

But

$$q = \int C\,dt = -\frac{1}{p} C_0 \cos \theta, \quad \text{where } \theta = pt = 2\pi n t.$$

Substituting, we get

$$R C_0 \sin \theta - \frac{1}{pK} C_0 \cos \theta = E.$$

Now divide both sides by

$$\sqrt{R^2 + \frac{1}{p^2 K^2}};$$

and call

$$\tan \phi = \frac{-1}{R p K}.$$

Then

$$\sin \phi = -\frac{1}{p K} \cdot \frac{1}{\sqrt{R^2 + \frac{1}{p^2 K^2}}},$$

and

$$\cos \phi = \frac{R}{\sqrt{R^2 + \frac{1}{p^2 K^2}}}.$$

$$C_0 (\cos \phi \,.\, \sin \theta - \sin \phi \,.\, \cos \theta) = E \div \sqrt{R^2 + \frac{1}{p^2 K^2}}.$$

$$C_0 \sin (\theta - \phi) = \frac{E}{\sqrt{R^2 + \frac{1}{p^2 K^2}}}.$$

This indicates that the volts will lag in phase behind the current; or in other words, the current will lead in phase.

Mean Power.—The mean power is obtained by integrating the power during one period and dividing by that period, and therefore may be written

$$\frac{1}{T}\int_0^T E\, C\, dt = \frac{1}{T}\int_0^T R\, C^2\, dt = \frac{1}{T}\int_0^T \frac{E^2}{R} dt.$$

If we square the expression [VII.] found for current and substitute for the square of the sine its mean value, viz. $\frac{1}{2}$, and then multiply by R we get as the mean power (in watts)

$$W = \frac{2 \pi^2 n^2 S_2^2 N^2 R}{R^2 + 4 \pi^2 n^2 L^2}.$$

This expression, by a well-known algebraic rule, will be a maximum for variations of R, when R is such that the two terms in the denominator are equal, or when the resistance equals the inductance. Under these circumstances the highest lag is 45°. But though this is the condition for highest plant efficiency, the regulation is, under these circumstances, bad. Hence it is better to use such a machine for lesser currents than those which would produce so great a lag.

Skin Effect.—When the frequency is high, there is a tendency for the alternate current to distribute itself unequally through the cross-section of the conductor, flowing most strongly in the surface parts. For this reason it has been proposed to use hollow conductors, or flat conductors, rather than solid round wires. But with frequencies not exceeding 100 periods per second, this tendency is negligibly small in copper conductors under one centimetre in diameter. Where the conductor is large, or the frequency high, the effect may be judged from the following instances calculated by Professor J. J. Thomson.[1]

In the case of a copper conductor exposed to an electromotive-force making 100 alternations per second, at 1 centimetre from the surface the maximum current would only be 0·208 times that at the surface; at a distance of 2 centimetres only 0·043; and at a distance of 4 centimetres less than $\frac{1}{500}$ part of the value at the surface.

If the electromotive-force makes a million alternations per second, the current at a depth of one millimetre is less than one six-millionth part of its surface value.

The case of an iron conductor is more remarkable. Taking the permeability at 1000 and the frequency at 100 per second, the current at a depth of one millimetre is only 0·13 times the surface value; while at 5 millimetres it is less than one twenty-thousandth part of its surface value.

[1] *Elements of the Mathematical Theory of Electricity and Magnetism* (Cambridge University Press.)

CHAPTER XXIII.

ALTERNATORS.

ALTERNATORS, or alternate-current dynamos, may be classified in three sorts :—

I. Those with stationary field-magnet and rotating armature.

II. Those with rotating field-magnet and stationary armature.

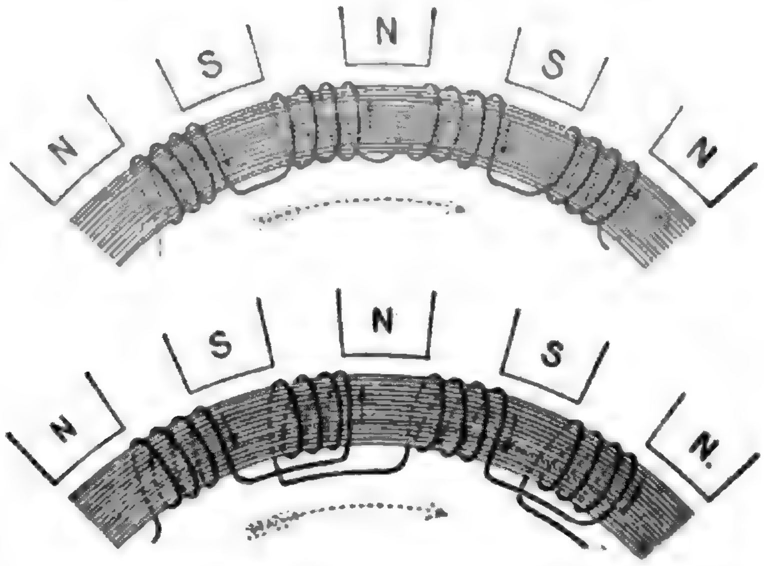
III. Those with both field-magnet part and armature part stationary, the amount of magnetic induction from the latter through the former being caused to vary or alternate in direction by the revolution of appropriate pieces of iron, called *inductors*.

Alternators may also be classified into *single-phase* and *polyphase* according to whether their coils are so arranged that the currents all rise and fall in them at the same instants, or whether they have two, three or more circuits so arranged that the currents in one part are out of phase with those in another circuit. The frequency used in practice varies between 25 periods per second to 100 or sometimes 150 periods per second; but each machine is expected to work at its own proper frequency. The symbol n, used for the number of revolutions per second in the formulæ for continuous-current dynamos, is also used, in formulæ for alternate currents for the number of *periods* per second, as it corresponds to the number of complete alternations there would be if the dynamos had but one pair of poles. For arc lighting it is impracticable to work with a lower frequency than 40, though lower frequencies are quite as good for motor driving. The higher the frequency, the smaller the transformers; but very high frequencies give trouble, increasing the inductive drop in the mains. As it is

requisite in alternate-current working to have so many alternations in every second, and as mechanical considerations forbid very high speeds, it is the general practice to make this class of machines multipolar, with a considerable number of poles of alternate polarity arranged symmetrically around a common centre. The number of symmetrical poles in machines of different systems varies from 12 to 48 or more.

The armatures of alternators may be of ring, drum, pole, or disk type; but the grouping of the windings is in general different from that which would be adopted for a continuous-current dynamo. The field-magnet being multipolar, a section of the armature winding which is passing a N-pole will have currents induced in it that circulate in an opposite sense to those induced in a section which is at the same moment passing a S-pole. Hence in an alternate-current ring the successive sections must be either wound or connected so as to be alternately right-handed and left-handed. In alternate-current drums the sections do not overlap one another as in ordinary drum armatures; nor do they overlap in alternate-current disk armatures.

Ring Armatures.—This type was invented in 1878, almost



FIGS. 372 and 373.—RING-ARMATURE SERIES WINDINGS FOR ALTERNATORS.

simultaneously by Gramme[1] and by Wilde,[2] the main difference between them being that, whilst Gramme rotated his

[1] Specification of Patent, 953 of 1878. [2] Ibid., 1228 of 1878.

field-magnet within a large stationary ring, Wilde rotated his ring-armature within an external system of inwardly-pointing field-magnet poles (see Fig. 101, No. 28). When ring armatures are used in this type of dynamo, they must not be wound in the same manner as for continuous-current armatures. If the successive sections are to be connected up in series then they must be wound as shown in Fig. 372, alternately with right-handed and left-handed windings. If all the sections are coiled right-handedly, then they must be connected as shown in Fig. 373; for the electromotive-force induced in a coil as it passes under a N-pole will circulate around the armature core in an opposite direction to that induced in the neighbouring coil that is passing under a S-pole.

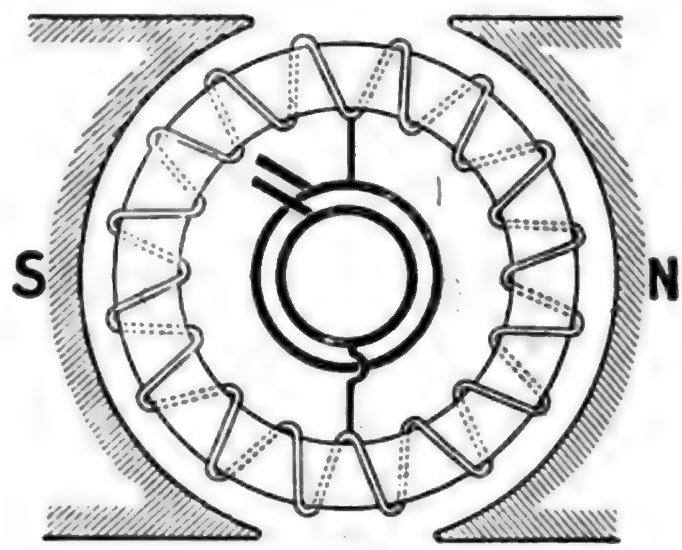


FIG. 374.—SIMPLE BIPOLAR RING ALTERNATOR.

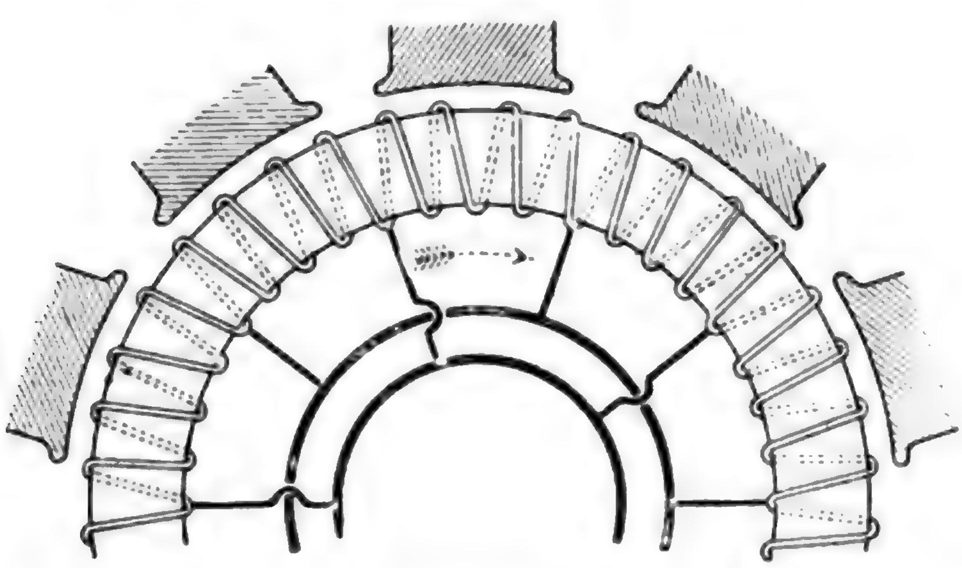


FIG. 375.—RING-ARMATURE PARALLEL WINDING FOR ALTERNATOR.

If a Gramme ring wound in the ordinary way is connected down to slip-rings from two points at opposite ends of a diameter, it will yield an alternating current when revolved in a bipolar field. In a multipolar field the ring will need

multipolar connexions alternately at points corresponding to the pitch of the poles. In this case, Fig. 375, the various sections of the ring are all in parallel.

A diagram of the Gramme alternator is shown in Fig. 376. The sections of the winding of this machine were four times as numerous as the poles, and might be coupled to feed four separate circuits. It is clear that the revolving poles would come past the four adjacent sections successively, so that the four alternating currents generated would differ *in phase* from one another. Gramme's was in fact a polyphase machine.

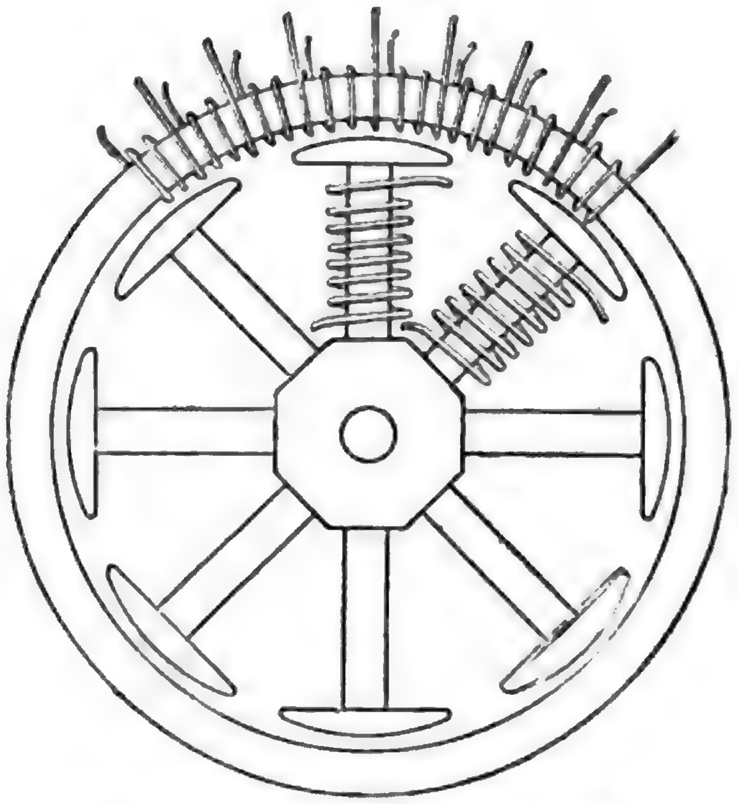


FIG. 376.—GRAMME ALTERNATOR.

One form of Gramme alternator, designed for use with Jablochkoff's candles, had four separate circuits differing 45° in phase from each other. Another ring alternator, by De Meritens, with permanent steel magnets, was a favourite about 1879. A ring armature with external magnet is used by Messrs. Ernest Scott and Mountain.

In Kapp's early alternator depicted in the former edition of this book, the ring lies between a double crown of field-magnet poles. Other ring alternators have been designed by Rankine Kennedy, who uses a discoidal ring between alternately-spaced alternate poles within an iron-clad magnet; and

by Mordey, who has suggested a form with two Pacinotti rings, one laminated, as armature, one non-laminated, as field-magnet.

Drum Armatures.—So far as the active wires are concerned, they may be coupled up quite as effectively without being wound around a ring core. In Fig. 377, which is a diagrammatic picture of the early Westinghouse alternator, the windings lay on the outside of a drum core; the sections being coiled separately in temporary frames and then laid upon the surface of the core, with the ends turned down over the end core disks and firmly secured.

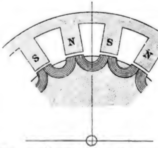


FIG. 377.—EARLY FORM OF WESTINGHOUSE ALTERNATOR.

In the recent Westinghouse machines the coils are held in deep slots in the iron of the armature. Large armatures are built up of segments, one of which is shown in Fig. 378, composed of thin mild steel stampings bolted together and assembled so as to form a core like the larger cores shown in Fig. 216, p. 288. The joint in the segments being made in the centre of a tooth does not affect the reluctance of the magnetic circuit. The coils, wound on formers, are at first of sufficient width to slip over the projections of the teeth. When in position their ends are nipped so that they fit closely and are held by the teeth from flying out. This construction is

FIG. 378.—WESTINGHOUSE CORE SEGMENT.

further illustrated in Fig. 401, p. 602, which shows the wooden wedges driven in longitudinally to make the whole compact.

Fig. 379 has an internal revolving field-magnet, and as armature an external cylinder built of segmental core-plates,

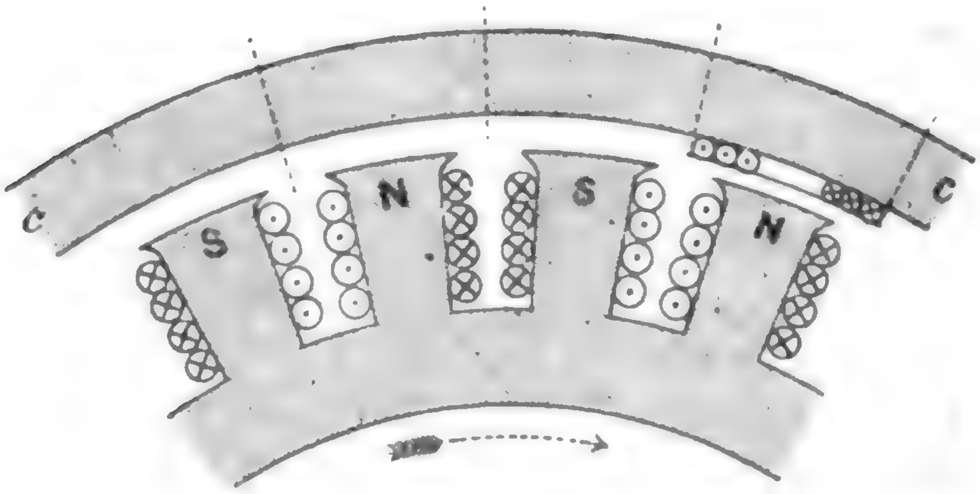


FIG. 379.—EARLY FORM OF ELWELL-PARKER ALTERNATOR.

against the inner periphery of which the armature coils are fastened.

It is but a step from this form to Fig. 380, which shows the construction of Zipernowsky, in which the field-magnet

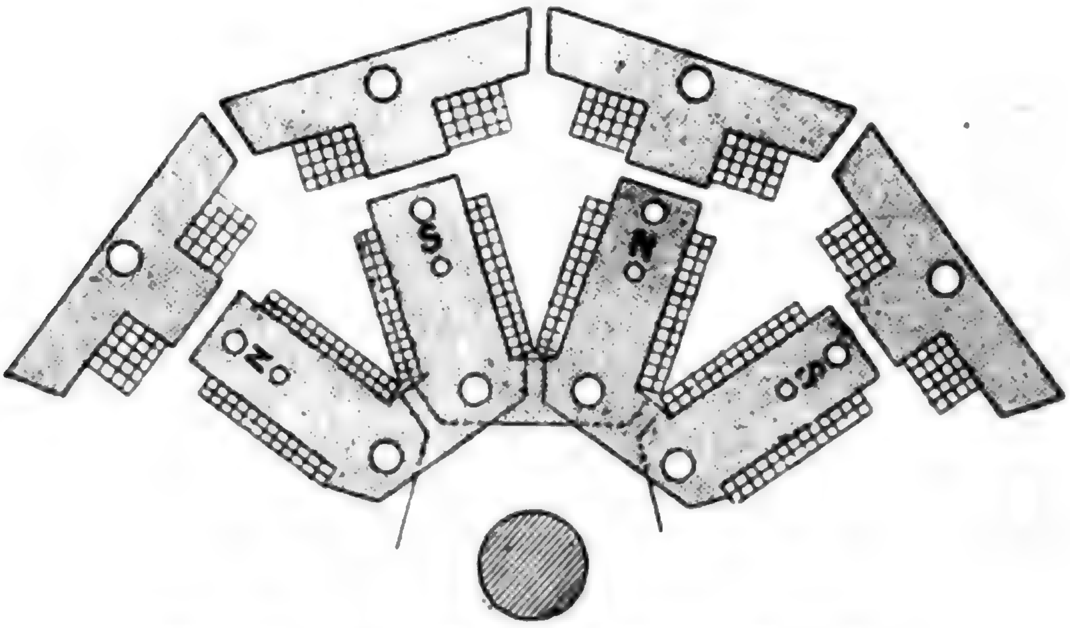


FIG. 380.—GANZ-ZIPERNOWSKY ALTERNATOR.

cores are made up of U-shaped stampings, and the armature cores of short T-shaped pieces which project through the coils, and are removable singly. We are thus passing away from the drum type toward that with *pole* armature.

Hopkinson's alternator, Fig. 411, p. 613, is an inversion of this design, the field-magnet being fixed and external.

Disk Armatures.—In these machines the armature coils are arranged around the periphery of a thin disk. The field-magnets consist of two crowns of fixed coils, with iron cores arranged so that their free poles are opposite to one another, with a space between them sufficiently wide to admit the armature, Fig. 383. The poles taken in order round each crown are alternately of N and S polarity; and opposite a N-pole of one crown faces a S-pole of the other crown. This description will apply to the magnets of the alternate-current machines of Wilde and Siemens, and to Ferranti's alternator. The principle will be best understood by reference to Fig. 381, which gives a general view of the arrangement. Since the magnetic lines run in opposite directions between the fixed coils, which are alternately S—N, N—S, as described above, the moving coils will necessarily be traversed by alternating currents; and as the alternate coils of the armature will be traversed by currents in opposite senses, it is needful to connect them up, as shown in Figs. 381 or 384, so that they shall not oppose one another's action.

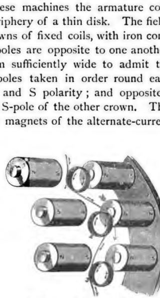
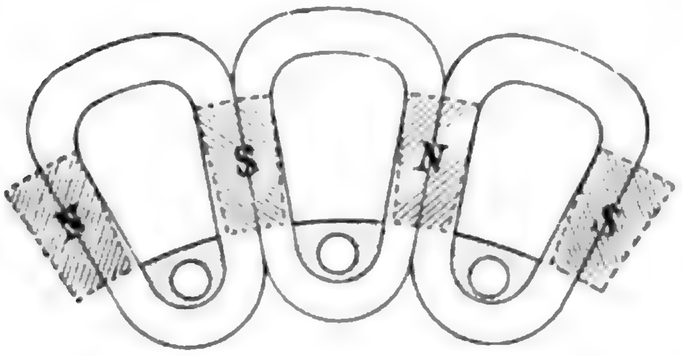


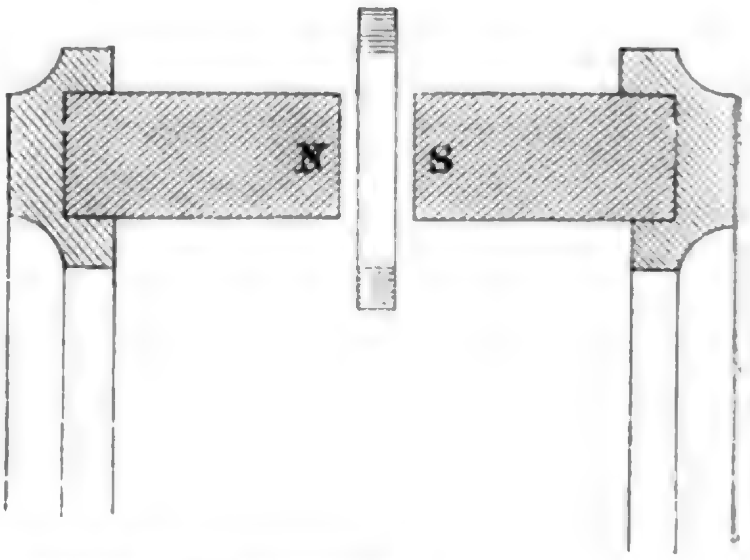
FIG. 381.—PRINCIPLE OF DISK ALTERNATOR.

Siemens' alternators, dating from 1878, realize this design with a thin disk armature built up of wedge-shaped coils. Ferranti's alternators follow the same plan, the copper coils being built up into a thin disk, as indicated in Figs. 382 and 383.

Collecting Rings.—In those alternators in which the armature part is fixed, mere terminals are required for collecting the main current. In machines with rotating armatures

simple sliding connexions are needed. The usual method of collecting is shown in Fig. 384. Two undivided insulated





FIGS. 382 and 383.—FERRANTI ALTERNATOR.

metal rings, forming the terminals of the armature coil, slide each under a collecting-brush.

Where high voltages are used the two slip-rings should be so placed that by no accident can an attendant touch both at

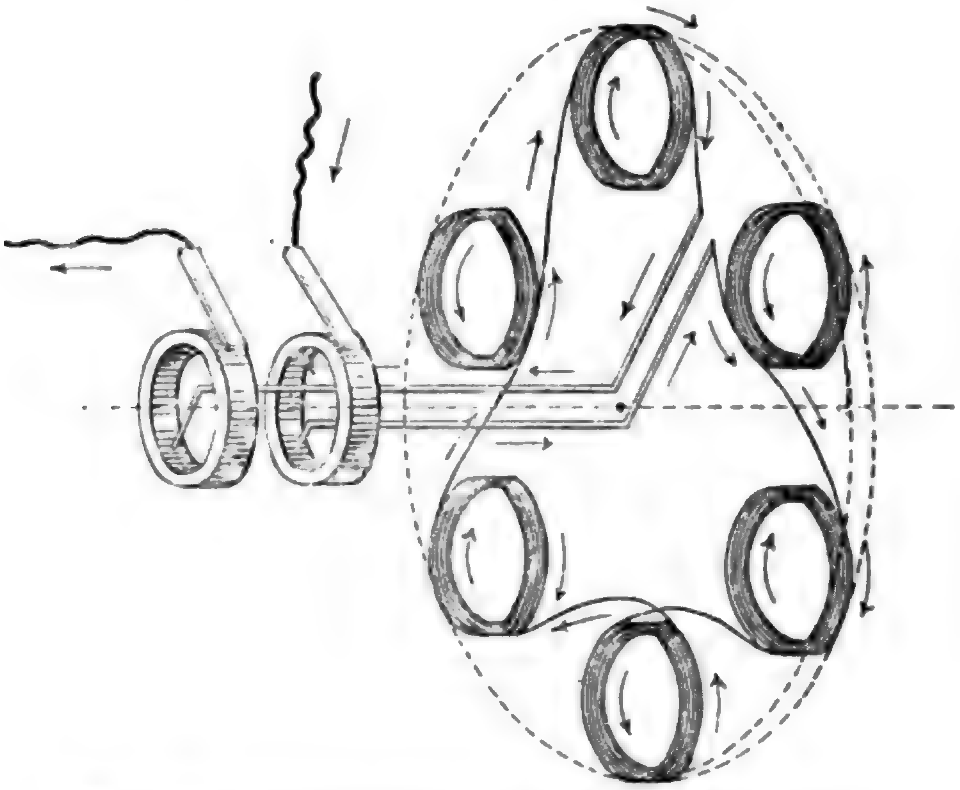
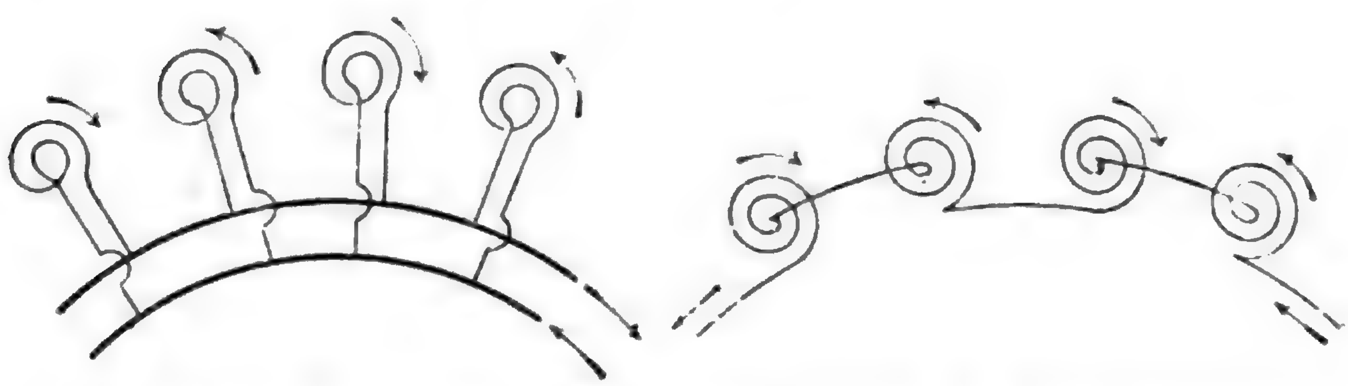


FIG. 384.—COLLECTING-RINGS OF ALTERNATORS.

the same time. It is also well to provide two brushes to each ring to make contact sure. For alternators with stationary

armatures a similar but smaller pair of slip-rings suffice to carry the exciting current to the revolving field-magnets.

Coupling Armature Coils.—There are various ways of coupling up the coils of alternators, according to their purpose. For low-voltage work the coils may be coupled up in parallel as in Fig. 385, so as to reduce the internal resistance; whilst for supplying distant transformers and for transmission of power, in both of which cases high electromotive-force is required, the more usual mode of connecting is to join the several coils in series, as in Figs. 385 and 386.



FIGS. 385 and 386.—DIFFERENT MODES OF COUPLING UP ARMATURE-COILS OF ALTERNATORS.

Comparison of Continuous and Alternate-Current Winding.—We have seen above in the case of ring windings how a system of parallel grouping could be reached by connecting down at appropriate intervals. Precisely similar considerations apply in the case of drum windings. For instance, a 10-pole armature with 360 conductors might be wound as a re-entrant lap-winding by connecting forward at one end of the drum over a spacing of 37, and then lapping back at the other end over a spacing of 35. This is just what might be used with a 180-part commutator for continuous currents. But suppose no commutator added, and ten connexions brought down at regular intervals (as in Fig. 375) to two slip-rings: it will then serve as an alternate-current armature. Instead of using this lap winding, the 360 conductors might be grouped in 10 lots of 36 each, each lot of 36 being connected (like Fig. 377), as a pancake coil, opposite a pole, and then all 10 put in parallel as before. We shall consider later the effect of concentrating the

coils around polar points, as distinguished from the *distributive* winding where they are spaced out equally. If we wanted to use a wave-winding, the number 360 will not suit for a 10-pole machine. We must choose 358 with a spacing of 35 and 37 alternately. As this winding is in series with two circuits only in parallel we shall need only two connexions to the slip-rings from points equidistant along the winding.

Width of Pole-faces and Breadth of Armature Windings.

The distance from the centre of one N-pole to that of the adjacent S-pole may be called the *pitch* of an alternator. It is desired to know what is the best proportion for the pole-faces and the windings to bear to the pitch. This matter has been discussed by Kapp.[1] It involves two questions—(1) in what way will the voltage depend on the relative width of poles and breadth of windings; (2) what proportions will give the highest plant-efficiency. If the poles are too wide, so as nearly to touch, not only is there great leakage, but the coils must be inconveniently crowded. It is obvious that for any coil to give its best result it should be so large as to embrace the whole flux of magnetic lines from each pole as it passes. If it is smaller, it contributes less to the total voltage. If it is larger it merely takes more space. Hence it is usual to make the width of the internal aperture of the coils but little less than the width of the pole, and to make the external width equal to the pitch. Compare Figs. 377, 379 and 382, in the first two of which the inner width is rather less, and in the third rather greater than that of the pole-faces, whilst the double breadth of copper in the coils is about equal to the width of the poles.

It has been shown on p. 45 that the average electromotive-force of a continuous-current dynamo may be written

$$E = n \, Z \, N \div 10^8 ;$$

[1] *Proc. Institution Civil Engineers*, xcvii. 1889, pt. iii.

where n was the number of revolutions per second, Z the number of conductors around the armature, and N the magnetic flux. We may adapt this to alternators, whilst keeping the two former symbols, and using N for the magnetic flux through any *one* pole, by multiplying by p the number of pairs of poles, and by a coefficient k.

So we have

$$E \text{ (virtual volts)} = k\, p\, n\, Z\, N \div 10^8.$$

If the fluctuations followed a sine curve, so that the virtual volts were 1·1 times greater (see p. 555) than the average volts, and the coils all joined in series (instead of two parallels), then k would have the value 2·2. The value[1] of k for various widths of poles and breadths of coils has been calculated by Kapp, with the following results; the field under each pole being supposed uniform:—

Pole Width.	Total Breadth of Copper in Coil.	k
1. Equal to pitch	Equal to pitch (covering whole surface)	1·160
2. Equal to pitch	Half of pitch (covering half surface)	1·635
3. Half of pitch	Equal to pitch (covering whole surface)	1·635
4. Half of pitch	Half of pitch (covering half surface)	2·300
5. Third of pitch	Third of pitch (covering third of surface)	2·830

If there were no spreading of the magnetic field, No. 4 of these would be best (being also nearest sine-law). On a smooth core such as Fig. 377 or Fig. 379, the useful breadth of wires is that which would just lie between the pole-tips. The output of a machine having a given thickness of copper in the gap is proportional to the number of such wires and to the width of the pole-face; therefore to the product of the two breadths, the sum of which (if there were no magnetic spreading) would equal the pitch. Hence the output would be a maximum when the breadth of coils and width of poles

[1] See also Brousson on "The Determination of the E.M.F. of Alternators," *Elec. World*, 1895, xxvi. 236.

were each half the pitch. But Elihu Thomson has found by experiment that, owing to the distortion of the magnetic field when the machine is running, there is an advantage in making the breadth of copper greater than this; this is by diminishing the aperture of the coils to something less than one-half the width of the pole-face.

Let us consider more closely the effect of breadth of the windings in the coils of the armature. Consider a multipolar revolving field-magnet, such as Fig. 387, in which we will assume that the pole-pieces have been so shaped that the magnetic field in the gap-space between poles and armature cores is distributed in a manner so as to give a regular and smooth wave-form for the curve of electromotive-force induced in any one conductor placed in the gap. We will represent electromotive-forces which act upwards, or towards the reader,

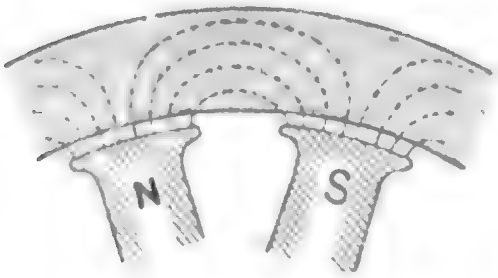


FIG. 387.

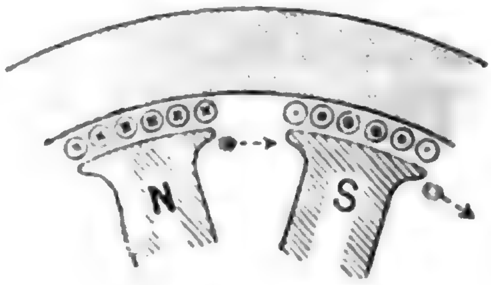


FIG. 388.

by a dot, and those which act downwards, or from the reader, by a cross placed in the section of the conductor. Then it is obvious that there will be induced electromotive-forces acting upwards in those conductors in front of which the S-pole is moving to the right, and downwards in those which the N-pole is passing. But these electromotive-forces will not be equal at the same instant amongst themselves: they will be greatest in those conductors which are most active, that is to say, in those which are passing through the strongest magnetic field. Each conductor will go through an equal cycle of inductive action, but it is clear that they come to their maximum one after the other. For convenience we will suppose this maximum to occur in each conductor as the middle of the pole passes it. Now suppose (as is usual in construction) that a number of these conductors are connected

up, as in Fig. 389, to form a coil; their electromotive-forces will be added together. If a view is taken, as in Fig. 389, where we are supposed to be looking back at the poles passing from right to left, we shall understand this a little more plainly. A moment later the N-pole will come right behind the coil as in Fig. 390. This figure shows that there can be no advantage in having the inner windings of the coil much nearer together than the breadth of the pole-face, since at this instant their electromotive-forces are opposing one another. But the actual electromotive-force generated by a coil of a given number of turns would be greater if they could be all of the same size, so that all should reach their maximum action at the same instant.

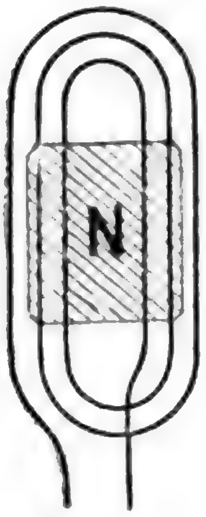


FIG. 389.

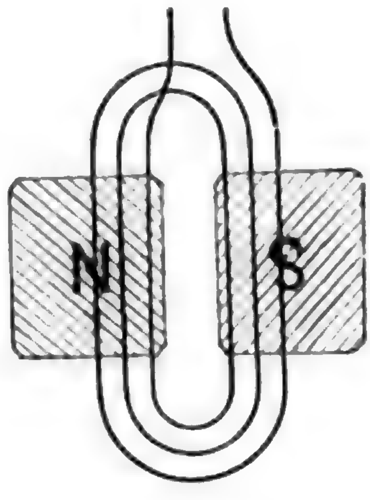


FIG. 390.

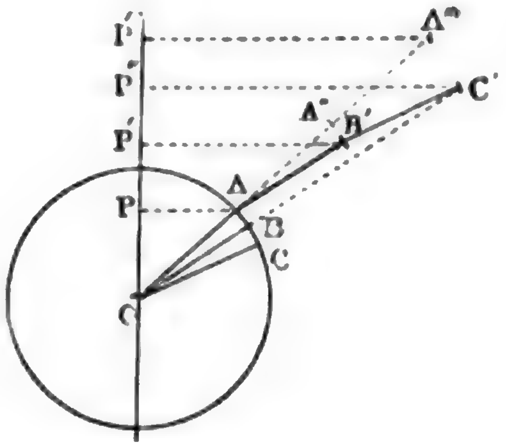


FIG. 391.

This point may be further elucidated by the use of a clock diagram. Suppose the maximum electromotive-force generated in one conductor to be represented by the pointer O A in Fig. 391. Then the projection of O A upon the vertical line O P gives the value of the electromotive-force at the instant when the angle A O P corresponds to the phase of the induction that is going on in the period. Let there be two other conductors situated a little further along so that these electromotive-forces would be represented separately by O B and O C. We have to find what the effect will be of joining them all in series. By the rules for compounding vector quantities, we shall find their resultant by drawing from A the line A B′ equal and parallel to O B, and from B′ the line

B′ C′ equal and parallel to O C. Then O C′ is the resultant; and its projection O Q upon the vertical line gives the instantaneous value of the united electromotive-force of the three conductors. Had they all been placed close up to one another at A without any difference of phase between them the resultant would have been O A‴, and this projected upon the vertical line gives O F‴ as the instantaneous value.

A numerical way of considering the matter may be useful. Suppose each conductor to generate an electromotive-force, the virtual value of which is 1 volt: then if three such conductors are connected up in series their total electromotive-force cannot be 3 volts unless they lie so close together that they all receive their maximum values at the same time. Any spreading out of the coils *must* lower the value of the resultant electromotive-force.

It is therefore worth while to calculate a breadth-coefficient for a coil of any particular angular breadth. Let the symbol ψ stand for the difference of phase between the centre of any coil and its outermost conductor on either side. If the machine has a 2-pole magnet the value of ψ is simply half the angular breadth (in radians) subtended by the coil. If the machine is multipolar, having p pairs of poles, then the angle ψ of the phase-difference will be equal to half the angular breadth (as measured on the machine) multiplied by p. Or, if the linear breadth of the coil measured along the circumference be called b, and the diameter of the machine is d, the angle ψ of the phase-difference corresponding to the half-breadth will be $= bp \div d$. Now the average value of the virtual electromotive-force in all the conductors comprised within this breadth will be given by the formula

$$\frac{1}{\psi}\int_0^\psi e \,.\, \cos\gamma \,.\, d\gamma\,;$$

where e is the virtual value electromotive-force in any one conductor and γ is the angle of difference of phase between the E.M.F. in any conductor of the coil and the E.M.F. in the central conductor of the coil. If we call the part of this ex-

pression which depends on ψ the breadth coefficient, and denote it by q, then performing the integration we have

$$q = \sin \psi \div \psi.$$

In order to give some numerical values we may anticipate some of the constructions later shown. For instance, in a ring wound with four coils each covering one quadrant (as in Fig. 467),

$$\psi = 45^\circ = \text{radius} : q = 0{\cdot}90.$$

In the case of a ring wound with three coils, each covering 120°,

$$\psi = 60^\circ = \text{radius} : q = 0{\cdot}82.$$

In the case of a ring wound with six coils each covering 60°,

$$\psi = 30^\circ = \text{radius} : q = 0{\cdot}95.$$

As an example consider a multipolar 2-phase generator, having armature conductors carried through holes in the core disks, and having 12 equally spaced holes in the repeat from one N-pole to the next N-pole. In this case six of the conductors belong to one phase, six to the other, and each group will consist of three up and three down. The three in a group occupy one-fourth the whole breadth, or are equivalent to 90° on the circle of reference: but as the conductors are confined within holes, the virtual angular distance between the two outer conductors of the three is 60°, and the half-distance 30°; whence $q = 0{\cdot}95$.

There has been much controversy whether armatures should or should not have iron cores. Iron cores are certainly inadmissible in thin disk armatures, as they would inevitably jamb against the pole-faces. Owing to the high frequency of alternation, the loss by hysteresis in machines with iron cores becomes serious, unless the magnetization is kept down below 7000 lines per sq. cm., and even then is not negligible. On the other hand, there is more loss by eddy currents[1] in the copper in machines not having iron cores.

[1] See remarks by Elihu Thomson in comment on Kapp's paper, *loc. cit.*

MODES OF EXCITATION OF FIELD-MAGNETS.

In the older machines the field-magnets were either of steel permanently magnetized, or else electromagnets separately excited. About 1869 began the practice of making these machines self-exciting by the method of diverting a small current from one or more of the armature coils, which were for this purpose separated from the rest, this current being passed through a commutator, which rectified the alternations and made it suitable for magnetizing the field-magnets. This device is used in the "composite" alternators of the Thomson-Houston (General Electric) Co., and in those of Ganz, who also attains the effect of compounding by supplying the field-magnets with a rectified current obtained by a small transformer from the main current, to which it is proportional. Such rectifying communicators have in general the form depicted in Fig. 392, consisting of two metal cylinders cut like crown-wheels, having the teeth of one projecting between the teeth of the other.

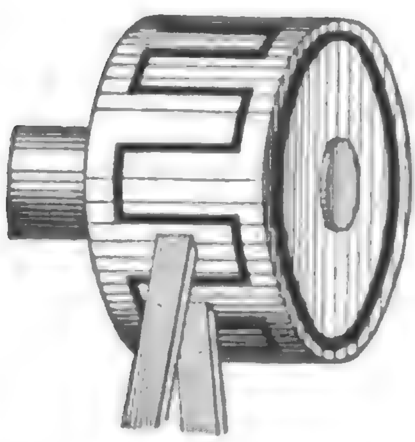


FIG. 392.
RECTIFYING COMMUTATOR FOR SELF-EXCITING ALTERNATORS.

They are insulated from one another, one being connected to one end of the wire of the armature coils that are to be used for exciting, whilst the other is connected to the other end of that wire. Two brushes are set so that one presses against a tooth of one, whilst the other presses against a tooth of the other part. An ordinary commutator having as many bars as poles may be used; the bars being connected together alternately into two sets. If the field-magnets are wound with fine wire, such a commutator may be used (in low-voltage machines) to rectify a fraction of the main current, thus making the machine virtually a self-exciting machine. It is, however, more usual to supply each alternator with a small auxiliary continuous-current dynamo termed its *exciter*.

A convenient way of regulating the current or potential of alternators is to interpose a variable resistance in the exciting circuit; the resistance being operated by hand or by some automatic regulator (see Chapter XXIX.). This method is applicable either to separately excited or to self-exciting machines. In the case where separate exciters are used, the performance of the alternator may be regulated by controlling (by variable resistances, &c.) the exciting circuit of the exciter.

Alternators, when intended for supplying glow-lamps at constant pressure, whether direct at low voltage, or by transformers at high voltage, are constructed with low resistance in the armature part. Those which have also a low coefficient of self-induction would be almost self-regulating if it were not for the demagnetizing influence of the armature currents. If the field is not *stiff* (p. 393) or if there is iron in the armature, or if the armature's reaction, as measured by the number of ampere-turns per pole, is too great, the machine will require much more excitation at full load than at no load. Even in the largest machines the armature ought not to create more than 3000 ampere-turns per pole. Those armatures that have the windings deep sunk between great teeth of iron have both great self-inductive drop, and great demagnetizing action at full load. For motor-driving alternators should be chosen which have no great inductive reaction. For supplying lamps in series with a *constant current* a somewhat different type of alternator is needed, having considerable self-induction in the armature. This is attained by winding the armature coils, deeply embedded in the core, or wound on long core-plates to give considerable magnetic inertia.

The demagnetizing influence[1] of the armature current is most marked when the field-magnets are weakly excited. In the Mordey alternator (p. 619) the field-magnet is so powerful that the diminution of the electromotive-force from this cause with the full current is less than 3 per cent. of the whole, the resulting droop in the characteristic being extremely slight. The demagnetizing action depends, however,

[1] See Esson in *Electrical Review*, xviii. 248, March 1886.

on the *phase* of the currents. If they neither lag nor lead, there will be no demagnetizing reaction, only a distortion of field (p. 75). But if they lag they will tend to demagnetize, while if they lead in phase they will help to magnetize the field. Swinburne[1] has discussed armature reactions from this point of view, and has suggested the use of condensers to produce an effect akin to compounding.

Some load-curves for an alternator have been given by Kapp (*loc. cit.*), and should be compared with Fig. 261, p. 380.

Now in an actual machine there are many armature conductors spaced symmetrically around, and these have to be grouped together by connecting wires or pieces. In the case of ring-wound armatures the connecting conductor goes through the interior of the ring-core, thus constituting a *spiral-winding*. When we go on to those cases in which the winding is entirely exterior to the core, as for drum armatures and disk armatures, we find that (as with continuous-current machines also) there are two distinct modes of procedure, which we may respectively denote as *lap-winding* and *wave-winding*. The distinction arises in the following manner. Since the conductors that are passing a north pole generate electromotive-forces in one direction, and those that are passing a south pole generate electromotive-forces in the opposite direction, it is clear that a conductor in one of these groups ought to be connected to one in nearly a corresponding position in the other group, so that the current may flow down one and up the other in agreement with the directions of the electromotive-forces. So after having passed down opposite a north pole face, the conductor may be connected to one that passes up opposite a south pole face, and the winding evidently may be arranged either to lap back, or to zigzag forward.

Wave windings were independently suggested in 1881, by Lord Kelvin and by Mr. Ferranti. But there are disadvantages in its use for high voltages, owing to the difficulty of maintaining the insulation between each "wave" and the

[1] *Journal Inst. Electrical Engineers*, xx. 173, 1891.

succeeding one. In some alternators—including those of Ferranti and Mordey—the coils are joined in two parallels, not all in series, a construction which has the result of keeping the points of greatest potential difference widely apart.

This distinction between lap-windings and wave-windings, as applied to alternate-current machines, is illustrated in

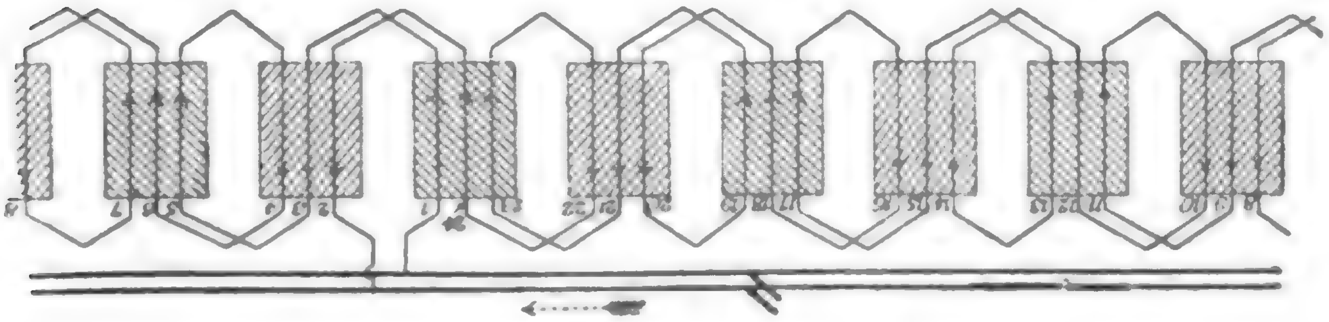


FIG. 393.—ALTERNATE-CURRENT MACHINE: LAP-WINDING.

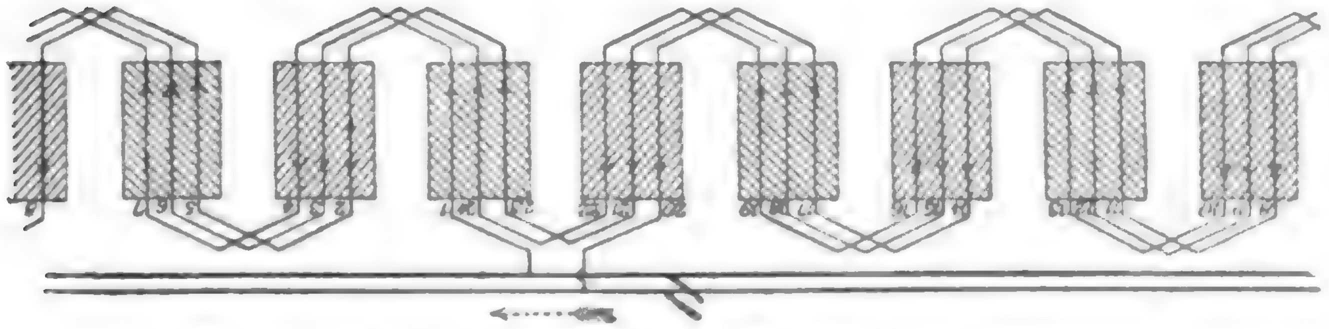


FIG. 394.—ALTERNATE-CURRENT MACHINE: WAVE-WINDING.

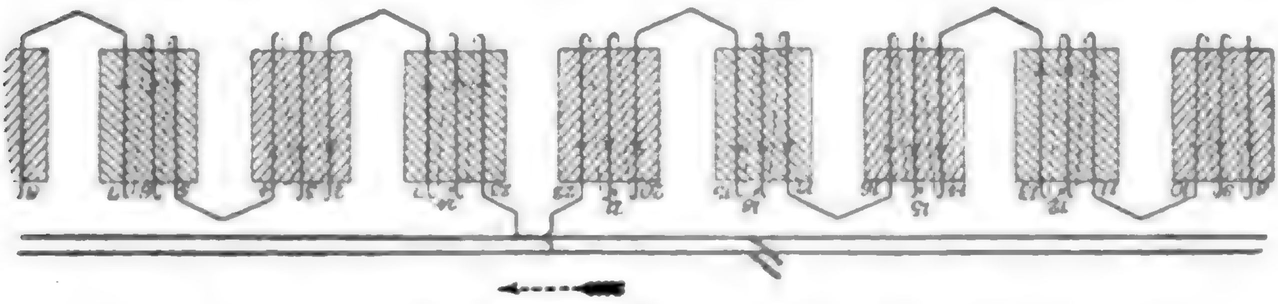


FIG. 395.—ALTERNATE-CURRENT MACHINE: RING-WINDING.

Figs. 393 and 394. Fig. 393 represents an 8-pole alternator with lap-winding, each "element" or set of loops extending across the same breadth as the "pitch" or distance from centre to centre of two adjacent poles. Only 24 conductors have been drawn; and it will be noticed that the successive loops are alternately right-handed and left-handed. In Fig. 394 is shown the same alternator with a wave-winding. The electromotive-force of the two machines would be precisely the same; the

choice between the two methods of connecting is here purely a question of mechanical convenience in construction and cost. The ring-winding using the same number of active conductors is shown in Fig. 395. In each case the beginning and end of the winding are connected to two slip-rings, which in these developed drawings are represented by two parallel lines. These therefore represent series or single-circuit windings.

Polyphase Alternators.—The disadvantage of making the coils broad, which was pointed out on p. 592, was experimentally discovered by Gramme. The closer the coils in any one group were huddled together, the more effective he found them. If, then, in his machine, Fig. 376, there had been only eight narrow coils—one opposite each pole—there would have been much idle space on the machine. Gramme, therefore, filled up the idle space with other coils. The sections of the winding of this machine were, in fact, four times as numerous as the poles, and might have been coupled to feed four separate circuits. It is clear that the revolving poles would come past the four adjacent sections successively, so that the four alternating currents generated would differ *in phase* from one another. Gramme knew or discovered that it would not do to join all the coils together. He only joined together those that at any one instant were opposite the poles. So there were four separate circuits each consisting of eight coils joined up in series. And these four separate windings were led off to four entirely separate circuits, each supplying a number of Jablochkoff candles with current. Gramme's alternator was unquestionably a *polyphase generator;* but there is not the slightest evidence that he at any time attempted to combine the currents of separate phases for any useful purpose, or that he knew that they could be so combined. On the contrary, he always kept the circuits separate because the several currents in them were not in phase with one another. No one, at that time, dreamed of combining currents of different phase so as to get a rotatory magnetic field.

It may be remarked, in passing, that in every type of

alternator there will be idle space between the groups of coils if they are wound advantageously for single-phase working.

If we make the armature with as many groups of windings as there are poles of the field we shall have a single-phase machine. If we make the coils twice as numerous as the magnetic fields we shall get a 2-phase machine. If they are three times as numerous a 3-phase machine.

The large alternators of the installation at Paddington, designed by the late Mr. Gordon (which were fully described in the first edition of this book), are 2-phase machines, with "red" and "blue" circuits kept separate. They have been at work ever since 1883.

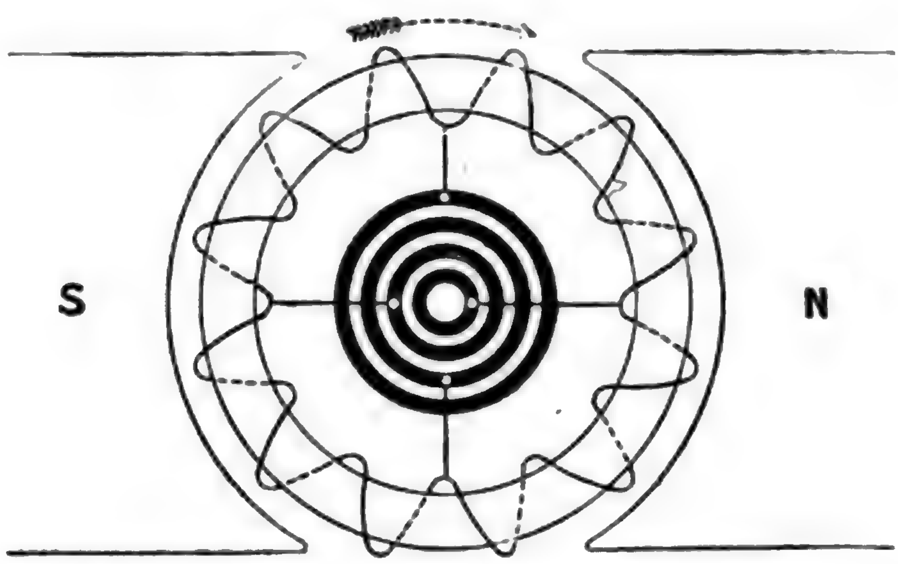


FIG. 396.—BRADLEY'S 2-PHASE GENERATOR.

A 2-phase alternator was designed by Bradley, in 1887, using in a bipolar field a ring connected at four points to four slip-rings (Fig. 396).

As the ring revolves the electromotive-forces tend always towards the highest point. Two separate alternate currents may therefore be taken from this machine, but they will differ by a quarter-period or be "in quadrature," as represented in Fig. 397.

A 3-phase alternator might have been made by connecting the ring to three slip rings at points 120° apart. Gramme indeed wound some of his rings with three independent sets of coils. Such a machine will yield three currents in three separate successive phases. If these were

grouped as in Fig. 398, we might join up the A coils together into one circuit (the coils being wound or connected alternately right-handedly and left-handedly); the B coils being similarly joined up into a second circuit, and the C coils being

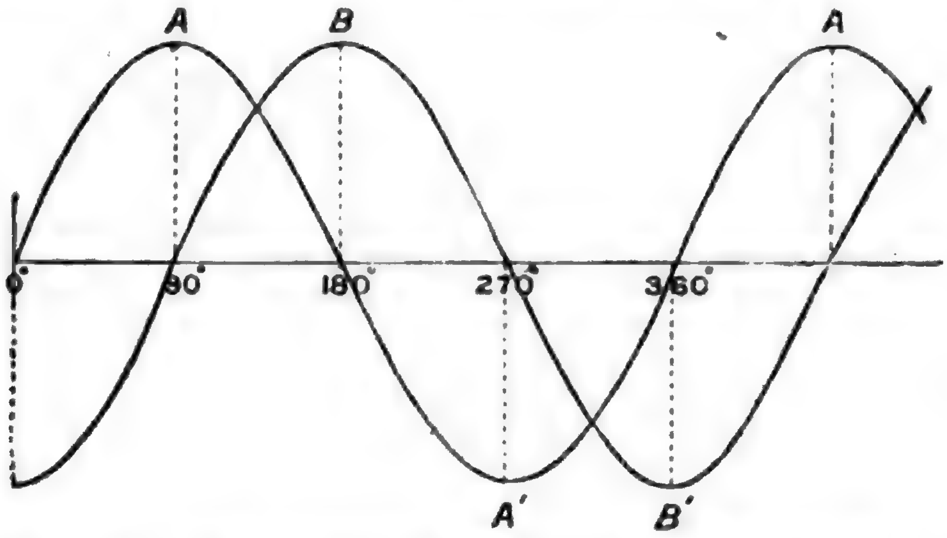


FIG. 397.—TWO ALTERNATE CURRENTS DIFFERING BY A QUARTER PERIOD.

joined into a third. It is clear that in each set the electromotive-forces would rise and fall in regular succession, and that the electromotive-force in B would not rise to its maximum until after that in A had passed its maximum and

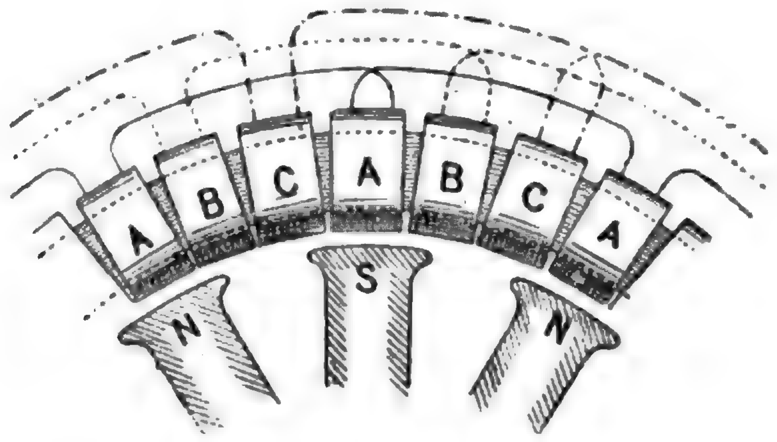


FIG. 398.—A 3-PHASE GENERATOR.

was falling. In fact the differences of phase might be represented by the three curves of Fig. 399. Since the angular distance around the machines from one N-pole to the next N-pole corresponds to one whole "period" (p. 549), or to one complete revolution of 360° on the imaginary circle of reference (Fig. 351), we see that these three currents will

differ in phase from one another by 60°. If we had a separate outgoing and return wire for each of the three circuits, we should need no fewer than six lines from the machine to the (3-phase) motor which it supplied. But as will be seen (p. 669), by adopting proper methods of grouping, this complication is unnecessary, the number of lines being capable of being reduced to four or to three. If an earth return were admissible the number of actual line wires might even be reduced to two.

Not only does the adoption of a polyphase winding lead to certain advantages in the operation of motors; it also effects

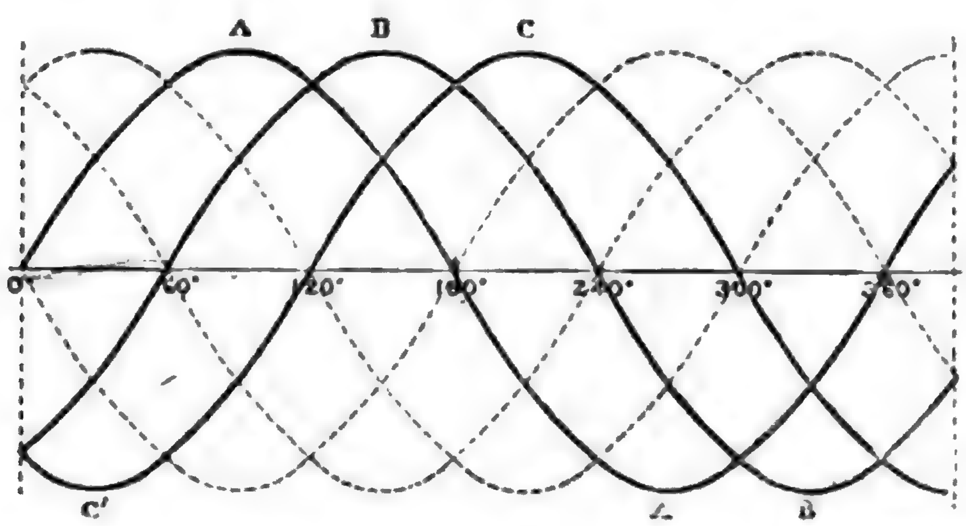


FIG. 399.—THREE-PHASE CURRENTS DIFFERING 60° IN PHASE.

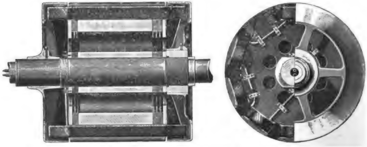
a saving in the cost of the machines. By winding a second set of circuits on the otherwise idle spaces on the core we may double the output of the machine. It will take twice as much horse-power to drive: it will give out twice as much horse-power electrically. But it will not cost twice as much, nor take up any more space. Goerges states that a 3-phase machine was found to give an output 2·73 times that of the same machine with a continuous-current armature.

CONSTRUCTION OF ALTERNATORS.

Although some excellent alternators have been made of the thin disk type by Siemens, Ferranti, Mordey and Crompton, there is at present an obvious preference on the

part of electrical engineers for machines of other types whenever large outputs are required. The racking strains to which the armature conductors are subjected render difficult the task of giving to the thin disk the mechanical strength it needs without sacrificing good insulation, or using constructions that would heat by reason of eddy-currents. Hence the majority of makers use iron core-disks in the construction of their armatures: and whether the armature revolves or stands still a sunk-winding is almost universal.

In Fig. 216 were shown some of the core-disks used by the Westinghouse Co. Those with a few large teeth are for alternators. Figs. 400 and 401 show the construction. The coils are wound on special formers and bent into their places; then secured by wooden wedge-pieces. In the largest machines the armature cores are built up of stampings assembled in sections, one of which is shown in Fig. 378. Fig. 402 shows a general view of a 450-kilowatt alternator of the Westinghouse standard type, having 30 narrow radial poles of elongated section surrounding an armature which is provided not only with the two slip-rings but with a rectifying commutator to furnish a small exciting current. The poles are of laminated steel cast solid into the outer yoke. The armature cores have 30 teeth to correspond. In many modern machines, however, the armature is fixed, and surrounds an



FIGS. 400 and 401.—SECTION OF WESTINGHOUSE ALTERNATOR ARMATURE.

internally revolving magnet. In this case the armature cores take in general one of the two forms shown in Figs. 403

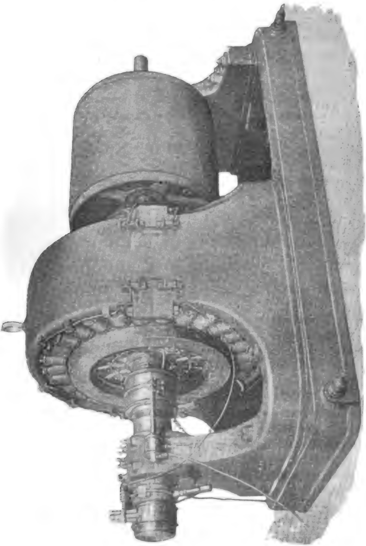


FIG. 402.—450 KILOWATT ALTERNATOR (WESTINGHOUSE CO.).

and 404. The pierced form is distinctively Swiss. Such core-rings are built up in segments, and may be wound in various ways. For low-voltage machines stout conductors may be drawn in and connected up in wave-form. For high voltages lap-windings are more usual, a number of turns being looped through two of the holes situated at a distance apart about equal to the pitch of the poles. Brown has introduced the practice of arranging these end parts of the loops where they emerge outside the core rings in two sets in different planes. This construction, which is applicable to all alternators whether for single-phase, 2-phase or 3-phase work, and to motors as well as generators, may be noticed in the coils in Plate XVIII. Though a detail it is of great use in obviating risks of short circuits. In Fig. 405 this construction is diagrammatically displayed, showing how both the A set and B set of windings in a 2-phase generator may be grouped so as to utilise for each lap two sets of holes side by side. This has some advantages over using single holes of very large size. These would interfere more with the magnetic circuit and tend to set up greater heating in the polar parts of the field-magnet.


Fig. 403.

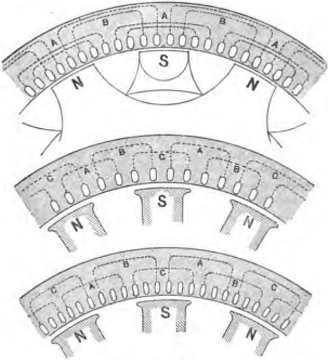

Fig. 404.

Fig. 406 shows an adaptation of the method of arranging the windings of a 3-phase generator, so that the loops of the coil can still be situated in two planes. The A coils will of course be connected together in series, though they lie alternately in the inner and in the outer positions; and so likewise the B and C coils.

Fig. 407 shows how the core-rings may be utilised for a 3-phase generator (or motor) with a winding in which all the holes are not employed. This winding was used to save

the necessity of making a fresh set of stamps for the core-disks. The magnetic reactions are less, when the unused holes are left in the spaces as shown, than would be the case if the core-rings at these parts were not pierced.

Another variety of the same construction may be noticed in Plate XVII., where one of the sections of the core is shown swung outwards for cleaning.



FIGS. 405, 406, 407.

In designing alternators the same general rules are to be followed as govern the design of continuous-current dynamos; but owing to the higher frequency of the reversals of magnetism a lower density of flux—say from 6000 to 7000—is to be observed in the laminated armature iron. The coefficient *k*, which comes in the fundamental formula, having been

determined by experiment in any given type, can be used in calculating machines of similar type. In calculating the excitation to be provided for the field-magnets, allowance must be made for the inductive choking action of the armature windings, as well as for the demagnetizing (p. 559) reaction of the armature currents; both these causes conspiring to produce an "inductive drop." Suppose an armature winding to have been calculated for 2000 volts on open circuit, at normal speed and field, and that the full current is to be 20 amperes. Some experiment must be made to ascertain the additional volts necessary to drive 20 amperes, not only through the resistance of the field but against its self-inductance. An experimental determination of this may be made by measuring with a voltmeter the volts actually needed (at the proper frequency) to send this current through the armature. Another and better experimental method is to short-circuit the machine through an amperemeter, and then drive it at the proper speed with field-magnets at first unexcited, gradually increasing the excitation until normal current is reached. Then open the circuit and measure the volts which at such excitation the armature generates. The next step after having found this reactive electromotive-force is to reckon out the additional excitation. Suppose that the experiment in question had shown the reactive electromotive-force to be 880 volts, then since they are in quadrature with the effective electromotive-force of 2000 volts, it will be needful that the impressed electromotive-force at full load should be at least

$$\sqrt{880^2 + 2000^2} = 2184 \text{ volts};$$

for which amount the full-load excitation must be calculated upon magnetic circuit principles. An example relating to a Kapp alternator was given on p. 656 of the previous edition.

Asynchronous Generators.—It has been found by several experimenters independently—amongst them Mr. C. E. L. Brown, and the engineers of the General Electric Company, at Schenectady, New York—that asynchronous motors (see p. 685), whether polyphase or monophase, can act as generators

provided they are mechanically driven at a slightly higher speed than that of synchronism. But it is not possible to work a circuit with only one such machine to be used as a generator—it is not self-exciting. There must be an alternate or polyphase current already supplied to the mains or terminals. It would probably be convenient in those central stations where the load is apt to show very sudden increase, to use one or more asynchronous generators along with other alternators, as the asynchronous generator might be kept turning as a non-loaded motor at a speed just below synchronism until required. On merely quickening up the speed of its engine (without waiting to "synchronize") it will begin to work as a generator, its electromotive impulses synchronizing perfectly with those of the circuit, though its speed is not synchronous.

EXAMPLES OF ALTERNATORS.

Gordon's Alternator.—Gordon's alternator was described and figured in the earliest editions of this book. It has twice as many coils in the fixed armatures as in the rotating magnets, there being 32 on each side of the rotating disk, or, in all, 64 moving coils; while there are 64 on each of the fixed circles, or 128 stationary coils in all. The latter are of an elongated shape, wound upon a bit of iron boiler-plate, bent up to an acute V-form, with cheeks of perforated German silver as flanges.[1] The result of thus arranging the coils in two sets, is that there are two distinct currents differing in phase by a quarter period. The Paddington station, equipped by Gordon in 1883, was the first 2-phase station.

Kapp's Alternators.—The multipolar ring-armature alternators of Kapp were described in detail in the previous edition, and scale drawings were given of a 60 kilowatt machine built at the Oerlikon works. More recently Mr. Kapp has designed a new alternator for Messrs. Johnson and Phillips. The construction is shown in Fig. 408. The

[1] For further details of the Gordon dynamo, see Mr. Gordon's *Practical Treatise on Electric Lighting* (1884), p. 162.

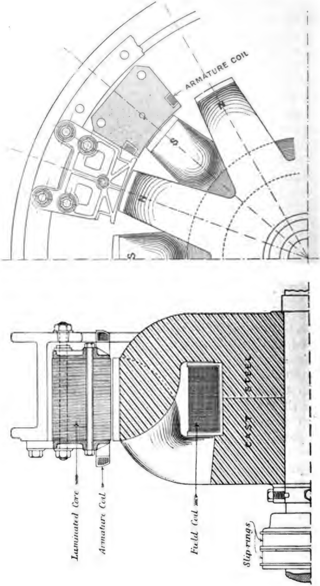


Fig. 408.—Kapp's Alternator.

armature core is built up of stampings assembled in removable segmental blocks. Around each block of core in end notches is wound a section of the armature coil. The armature consequently has considerable self-induction. The field-magnet is on the same plan as that of the Lauffen alternators described later (p. 631), having but a single coil for excitation.

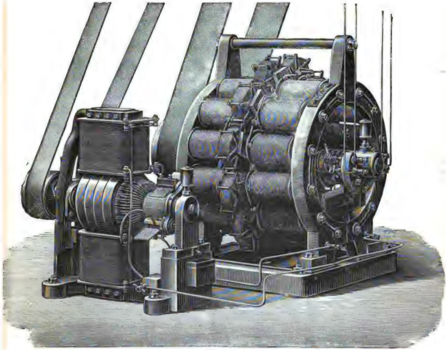


FIG. 409.—SIEMENS ALTERNATOR, WITH ITS EXCITER.

Siemens Alternators.—Messrs. Siemens and Halske were early in the field in 1878 with alternators designed by von Hefner Alteneck, having a disk-armature (see Fig. 409), in which the coils are wound usually without iron, upon wooden cores. Copper ribbons insulated from one another by strips of vulcanized fibre are used for the coils; the connexions

being made by soldering the strips with silver solder. In some forms of the machine, the individual coils are enclosed between perforated disks of thin German silver. In cases where large currents are required, at no great electromotive-force, the coils are coupled up in parallel instead of being united in series. In Fig. 409 a small continuous-current machine of vertical pattern, such as was described on p. 404, is shown in action as an exciting machine to furnish the magnetizing currents to the stationary field-magnets of the alternator.

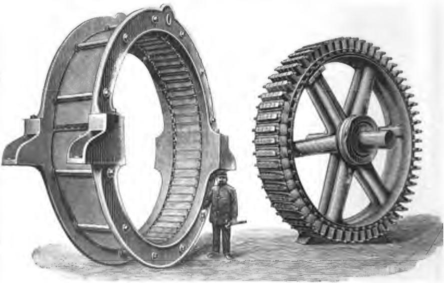


FIG. 410.—SIEMENS AND HALSKE ALTERNATOR.

More recently Messrs. Siemens and Halske have returned to a form with multipolar rotating field-magnet and fixed external armature. The large 330 kilowatt machine shown at Frankfort in 1891 is depicted in Fig. 410. The field-magnet consists of 60 bobbins with laminated cores built upon the rim of a fly-wheel, 3·7 metres in diameter over

all; whilst the armature ring is 4·6 metres (14 ft. 9 in.) in external diameter. When running at 100 revolutions per minute, it yields 165 amperes at 2000 volts. The construction of the armature is as follows:—A laminated ring of 60 segments, each built up of straight iron plates stamped with end-projections, is held together firmly in a cast-iron frame. Each segment before being put in place is wound with 20 turns of a conductor made of stranded copper wire compressed to a square section, each wire in the strand being lightly insulated with a coat of enamel. The ring thus formed is 4·6 metres in diameter, and 50 centimetres in width parallel to the axis; the end projections of the core-plates constituting 60 internal teeth. It is therefore simply a laminated Pacinotti ring with sections coiled alternately right and left-handedly. Any one of the sections can be removed singly for repair. The laminated magnet-cores carry 76 windings each, and receive a current of 56 amperes at 70 volts for excitation.

The large 3-phase alternators recently made for the central station at Chemnitz by Siemens and Halske, have a general construction resembling Fig. 406.

Ganz-Zipernowsky Alternators.—Various forms have been built[1] by Ganz and Co., of Buda-Pesth, chiefly from the designs of M. Zipernowsky. The general principle of these machines has already been described on p. 584; but some have been otherwise constructed. At Frankfort, in 1891, a large Ganz alternator was shown by the Helios Co.,[2] of a capacity of 400 kilowatts, giving 200 amperes at 2000 volts at 125 revolutions per minute. The armature consisted of 40 T-shaped punchings, like Fig. 380, surrounded with coils each working at 100 volts, the whole being coupled up in two series of 20 each. The rotating field-magnet is 299·2 centimetres in diameter, and 38 centimetres wide. The electrical efficiency

[1] See *Centralblatt für Elektrotechnik*, xii. 554, 1889; also *Electrical Review*, xv. 70, 1884; xvii. 115, 1885; *Electrician*, xxv. 258, 1890; *Electrical World*, xiii. 297, 1889; xvi. 73, 1890; *La Lumière Électrique*, xxxi. 121; and xxxii. 159 and 582, 1889.

[2] See description by Mr. Esson, and cut, *Electrical Review*, xxix. 503, 1891.

is given at 95·6, and the nett efficiency at 91·5 per cent. Four very fine examples of the Ganz alternator exist in the central station of Rome,[1] each being of 320 kilowatts capacity, driven direct at 125 revolutions per minute by separate compound engines of 500 H.P. each. They have rotating field-magnets with 40 radiating poles of solid iron, the diameter being over 9 feet. The interior diameter of the armature ring frame is about 9½ feet, the core being built up of sheet iron and paper as described. There are 40 coils, each generating 50 volts, all united in series, and capable of carrying 200 amperes, the wire being 6 mm. in diameter. The bobbins on which the magnet coils are wound, are made of split rectangular zinc formers about 15 inches high and 20 inches wide, the windings being more numerous toward the outer end. The armature windings, 30 in each coil, are contained on vulcanized fibre frames 19 inches long, 10 inches wide, and 2 inches deep, and are clamped in place by skeleton bronze frames.

Hopkinson Alternator.—This machine has fixed external multipolar magnets, with a width of pole-face exceeding three-fourths of the pitch. The armature wires are coiled upon short polar projections of laminated iron having extended faces. The machine is shown in Fig. 411. Its exciter is mounted on a bracket to run on the same shaft.

Owing to the almost complete continuity of the iron of the magnetic circuit, and the high peripheral speed which the construction of the machine admits of, an exceedingly high efficiency is obtained. The following are particulars of machines of this type constructed by Mather and Platt for the Salford central station.

No. of poles	20
Revolutions per minute	450
Output	40 amperes at 3000 volts.
Resistance of all magnet coils in series	7·4 ohms.
Resistance of armature coils in series	0·8 ohms.
Exciting current required through magnets at full load	10 amperes.
Hence *electrical efficiency* at full load	98·4 per cent.

[1] See description by Prof. Fleming in the *Electrician*, xxv. 317, 1890.

In spite of their high self-induction, these machines are suitable for working in parallel, and have so much armature reaction that they can be short-circuited with perfect safety.

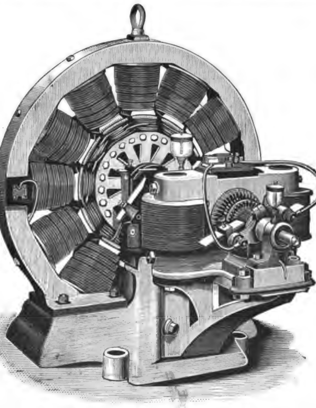


FIG. 411.—HOPKINSON ALTERNATOR (MATHER & PLATT).

Ferranti's Alternator.—This machine, as brought out in 1882, was based on the joint but independent proposal of Lord Kelvin and Mr. S. Z. de Ferranti to substitute wave-windings for coils.

In the machine as constructed at that date,[1] the field-

---

[1] See Specification of Patent, No. 3702 of 1883; and for later details, No. 702 of 1887.

magnet consisted of two crowns of alternate-poles, precisely as in the alternators of Wilde and Siemens; and the armature consisted of strip copper bent into a wavy star form. There were eight loops in the zigzag (as shown in Fig. 412), and on each side were 16 magnet poles; so that the current flowing radially outward past a N-pole flowed radially inward past a S-pole. The copper strip was wound round on itself (with insulation between) in many layers; the limbs of the star being held in place by insulated bolts passing through star-shaped face-plates. The advantage of the armature of zigzag copper was supposed to lie in its strength and simplicity of construction.

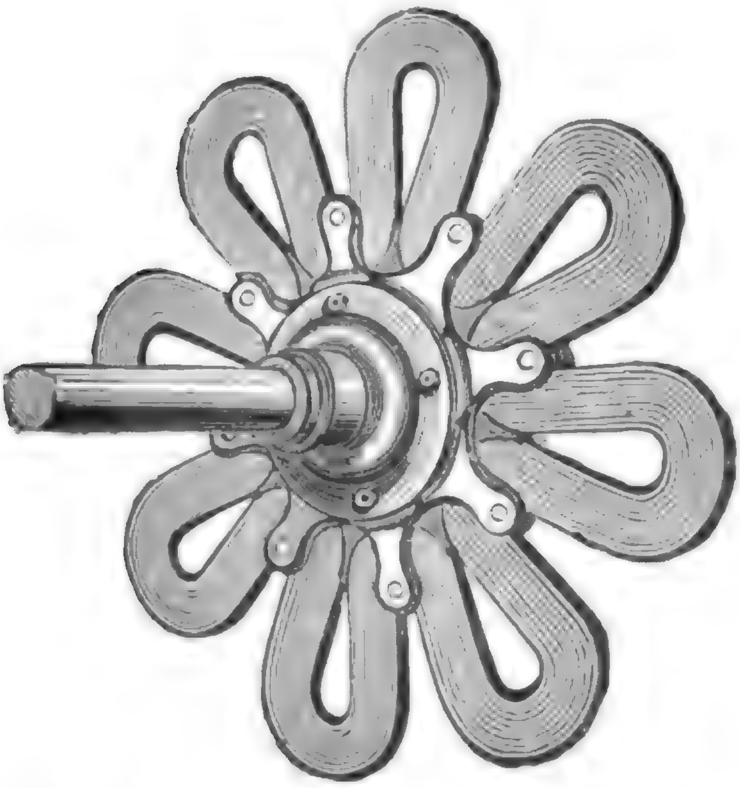


FIG. 412.—FERRANTI ARMATURE (1882).

In the later alternators of Ferranti the zigzag mode of winding has been entirely abandoned, and the coils are wound separately and then assembled into a disk. The mode of construction is explained by the figures which follow. Each coil is wound upon a rigid core. The cores are constructed of brass strips spreading fan-wise, with asbestos between, brazed solidly together at one end, and united to a brass piece drilled with an aperture A (Fig. 413). The winding, the inner end of which is soldered to the brass piece, is of ribbon copper slightly corrugated to secure greater rigidity, wound with a tape of thin vulcanized fibre between. The coils are mounted in twos in brass coil-holders, depicted at D, Fig 415, into which, with interposed layers of mica and fibre, they are secured by bolts which pass through their eyes. The two coils in each holder are separated mechanically and

electrically by interposing a piece of fibre of the form shown at H ; but the holder constitutes a metallic connection from the

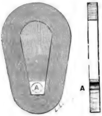


FIG. 413.—SINGLE COIL OF FERRANTI ARMATURE.

FIG. 414.
CONNEXIONS OF FERRANTI ARMATURE.

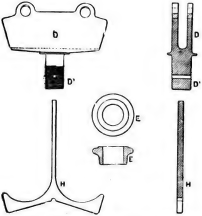


FIG. 415.—DETAILS OF FERRANTI ARMATURE.

eye A of the one to the eye A of the other. Consequently, a current circulating from outside to inside of one coil must

circulate from inside to outside of the other. The outside end of each coil is joined to the outside of the nearest coil in the next holder. The holders must of course be insulated, and yet held mechanically and firmly. For this purpose they are provided with a tail-piece D′, of circular section, which passes through a porcelain bush E, and is threaded to receive a metal foot which is further secured by a pin passing through D′. The tail-piece, protected by its porcelain bush, passes through the rim of a strong foundation ring, having apertures into which the metal feet are inserted, but which are much wider and longer. The gap between them is then filled up by pouring in a molten compound of sulphur and powdered glass, which secures and insulates them. On the side of each coil-holder projects a small oblique wing, to promote ventilation. In all the larger machines the coils are connected up, as shown in Fig. 414, in two series, which are joined together in parallel. This grouping is effected by placing all the coils in one half circumference right-handedly, and in the other left-handedly, and is adopted so as to keep widely apart the coils that differ most in their potentials.

FIG. 416.—FERRANTI ARMATURE, SHOWING MODE OF MOUNTING COIL-HOLDERS.

Two copper rods pass inwards from the tail-pieces of two of the coil-holders at opposite ends of a diameter, and are led

to the collecting arrangements which are mounted on the end of the shaft.

Fig. 417 relates to a 225 kilowatt Ferranti alternator, and gives a view of half the armature and half the field-magnet. Here it is seen how the copper connector D^2 passes from

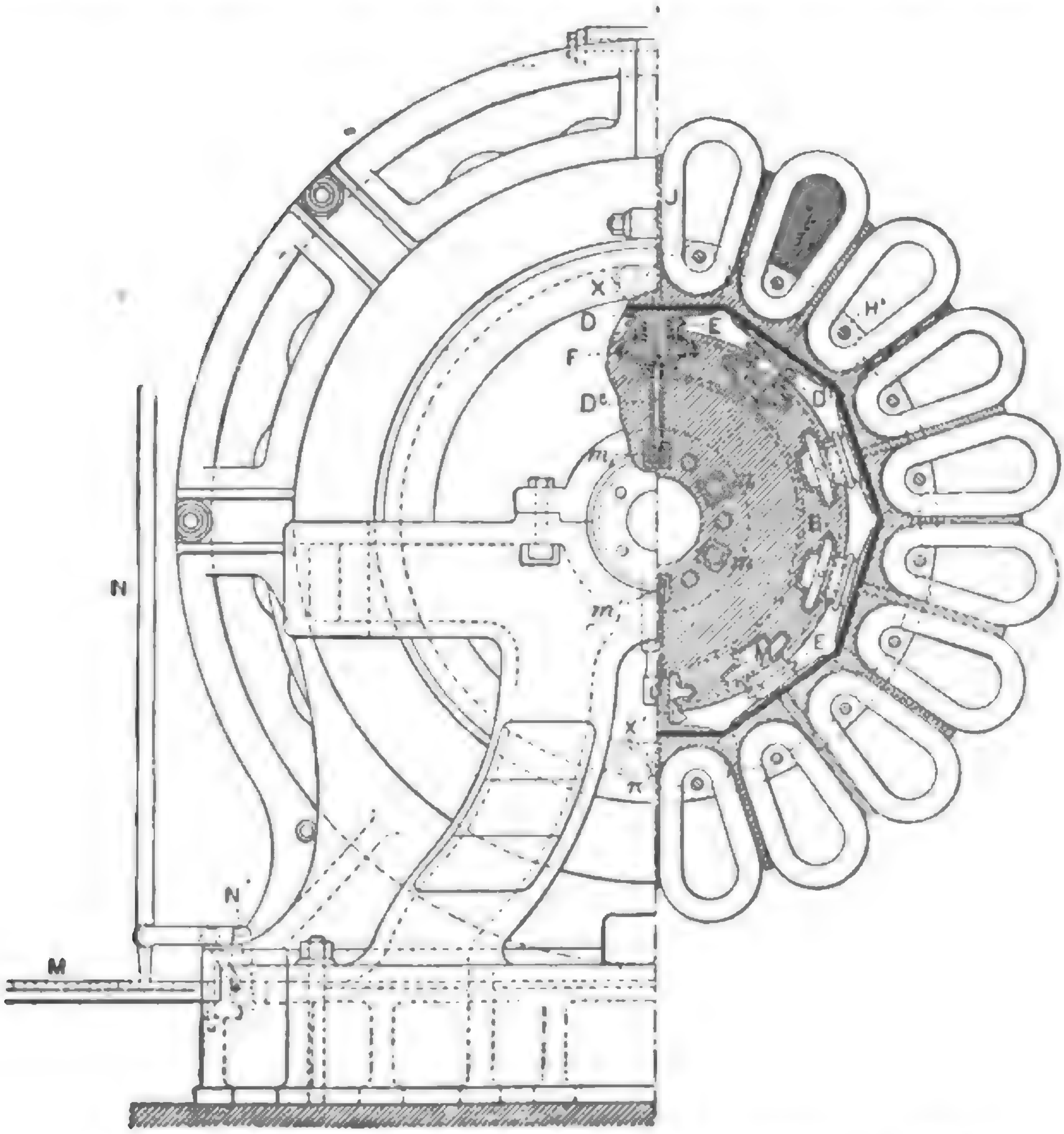


FIG. 417.—FERRANTI ALTERNATOR (225 KILOWATTS). Scale $\frac{1}{30}$.

the coil-holder D to m_1, a bolt uniting it to the collecting apparatus. The cut also shows how the field-magnet is built in two separate halves, each of which can be racked laterally aside by a lever N and rack M to expose the armature for cleaning or repairs. The speed of this machine is 350 revolutions per minute, and the diameter of the armature 5 feet 6 inches.

Fig. 418 represents on a scale of 1 : 72 the 1000 kilowatt alternators as used at the Deptford lighting-station. These machines, capable of giving 100 amperes at 10,000 volts, when running at 120 revolutions per minute, are driven by rope-gearing from engines of marine type. The pulley, which has grooves for 27 ropes, is nearly 10 feet in diameter, and over 10 feet long. It is built in two parts N and N_1, united by bolts at *a*, and is keyed to the middle of the shaft

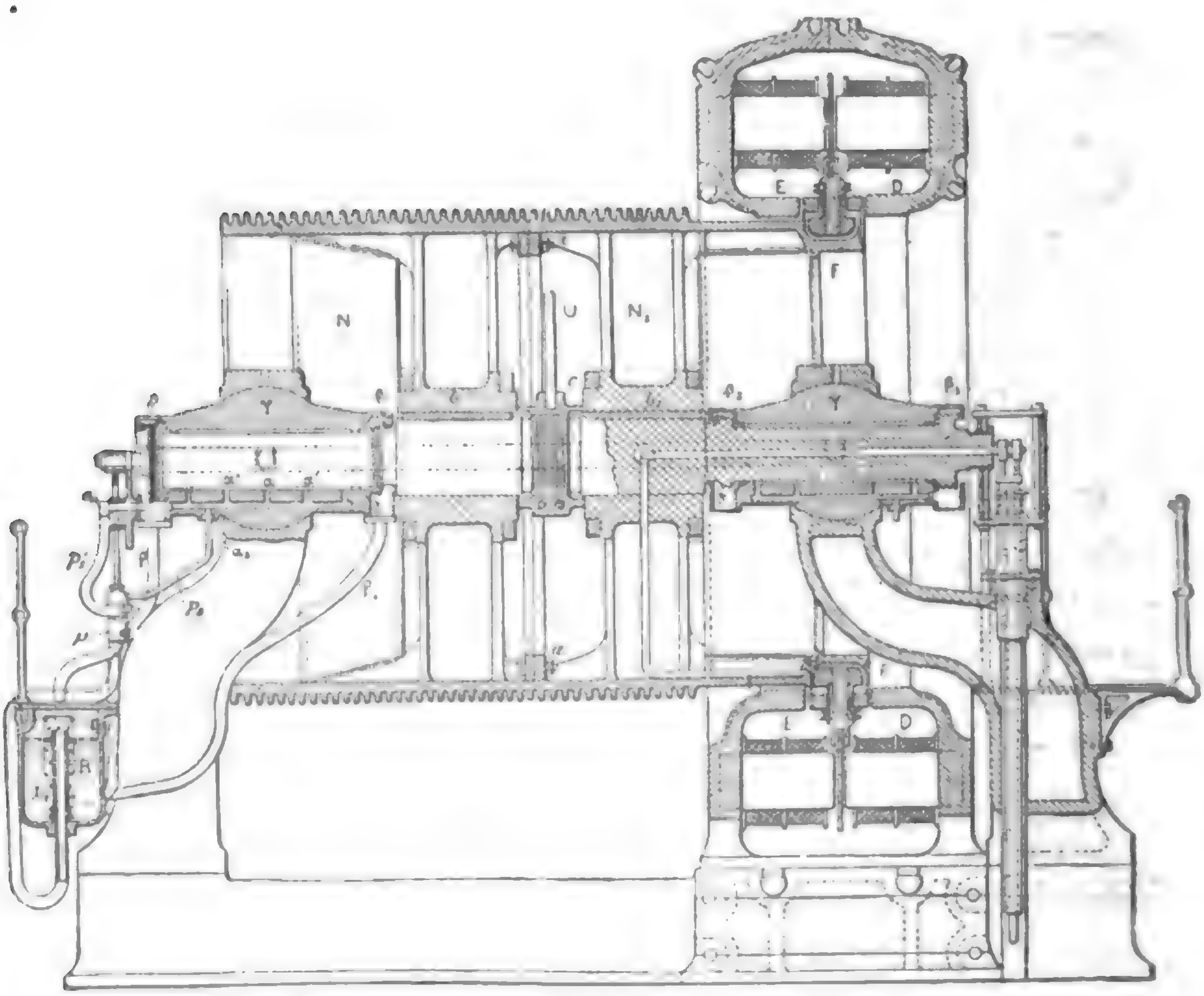


Fig. 418.—Ferranti Alternator (1000 kilowatts). Scale $\frac{1}{72}$.

between two bearings γ mounted on pedestals which curve inwards at both ends. The journals are of unusual length, and the bearings swivel upon spherical seats. End play is prevented by collars at the outer ends of the shaft. The exact position of the pulley upon the shaft can be adjusted by a central screw collar *c*, turned by a handle U. This adjustment is rendered necessary because the armature is mounted upon the end rim F of the pulley itself, over-

hanging the bearing; and, as the clearance between the armature coils and the magnet pole-faces is very small, any wearing of the bearings might cause the armature-coils to come dangerously close to the pole-faces. The coil-holders and porcelain bushes are shown at D and E. The magnet-poles are held in a large external cast-iron frame. There are 48 poles in each crown, of alternate polarity. The faces are covered with caps of thin ebonite to protect against spark discharges from the coils. The armature coils, also 48 in number, are each capable of generating about 420 volts, and will carry a current of 50 to 55 amperes without undue heating. The mean diameter of the armature is 15 feet, and its peripheral speed is therefore 5850 feet per minute. The thickness at the working part is only ¾ inch. Owing to the mode of driving the armature the insulated copper connexions must pass through the bearing, and are therefore carried along in a channel through the shaft. The most elaborate precautions are taken against the possibility of a stoppage arising from over-heating of the bearings. There is a double circulation of water and of oil. On the end of the shaft opposite to the collecting apparatus an eccentric works an oil-pump *p*, which pumps oil through a filter out of the reservoir R under the platform, and distributes it under pressure to the oil-ways *a* in the bearings, whence it returns to the reservoirs.

The alternators lately constructed by Mr. Ferranti for the Portsmouth central station[1] are of entirely different construction, and follow very closely the lines of Brown's machine, Plate XVII.

Mordey's Alternator.—This striking form of machine, first brought out in 1888, is constructed by the Brush Electrical Engineering Company, of London. One of small size is depicted in Fig. 419, while on Plate XIV. are given drawings of one of the 200 kilowatt machines,[2] lately erected at the Leicester lighting station.

[1] See *Electrician*, xxxiii. 157, 1894.

[2] See *The Engineer*, lxxx. 57, July 19, 1895. The figures given in Plate XIV. have been reproduced from this article.

The characteristic features of the Mordey alternator are the stationary thin-disk armature, and the solid revolving field-magnet. In the latter, though there are two crowns of

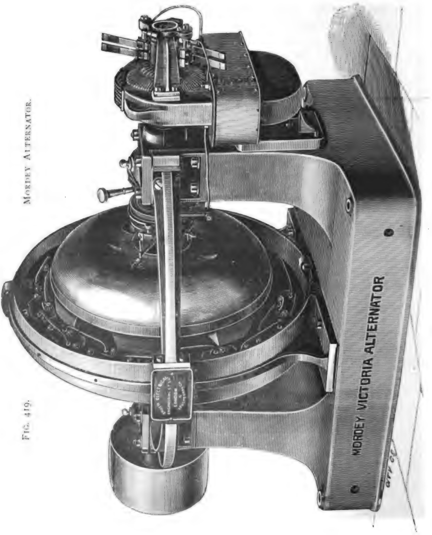


Fig. 419. Mordey Alternator.

poles between which the armature lies, all the poles on one side are of one kind, north poles, and all those on the other side are south poles. Hence there is no reversal of the magnetic field through the armature coils; the number of magnetic lines through any coil simply varying from zero to maximum and back. As a result of this arrangement, there is a great simplification of the means needed to magnetize the field-magnets. One single coil surrounding a central cylinder of iron suffices to magnetize the whole of the poles. There is indeed only one magnetic circuit, branching into separate branches. The construction of the field-magnet is as follows:—

A pulley-shaped iron cylinder, through which the shaft passes, forms the core, and is surrounded by the exciting coil. Against the ends of this core are firmly screwed up the two end castings (Plate XIV. Fig. 3) each of which is furnished with a number of polar projections varying from 9 in small machines to 60 in large ones, projecting toward one another; the narrow polar gap between them being only just wide enough to admit the armature. The entire field-magnet revolves on the shaft, the exciting coil being supplied with current from a separate machine by means of two contact rings on the shaft. There is no need for the exciting coil to revolve; but for mechanical reasons it was deemed preferable to wind it actually upon the field-magnet core. The armature coils are of copper ribbon, wound upon narrow wedge-shaped cores of enamelled slate, and insulated with a thin tape between the turns. Each coil is held in a German silver bracket embedded in ebonite and firmly clamped to the exterior frame. All the metal clampings are outside the magnetic field, and are so arranged that any one coil can be removed in a few minutes without dismounting any other part of the machine.

As the armature is stationary there are no centrifugal forces to be considered, and the coils have to be supported only with a view of resisting the tangential drag of the field. The revolving field-magnet forms an excellent fly-wheel, and as there are no parts liable to fly out, a high speed of driving presents none of the difficulties that arise with many

other types of machine. The journals are furnished with a shoulder to limit end-play, and the bearing blocks are made adjustable longitudinally, so that the field-magnet may be placed exactly symmetrically with respect to the armature. The electromotive-force is 1 volt per $8\frac{1}{2}$ inches of conductor. The very low resistance of the armature, and almost complete absence of armature reactions, makes the machine almost self-regulating, a point of some importance for parallel running, and for operating motors.

In some cases a small continuous-current machine is mounted on the same shaft as shown in Fig. 419, to excite the field-magnets.

Owing to the excellent conditions of ventilation, it comes about that the limit of current-density is not fixed by risk of overheating, but by considerations as to efficiency and self-regulation. The amperage at full load is no less than 3300 amperes per square inch. Loss by hysteresis there is none, owing to absence of any armature core. The eddy-currents in the conductor are trifling: the copper tape needing no further lamination. The coil-holders, moreover, are of German silver, the high specific resistance of which alloy reduces the losses by eddy-currents to $\frac{1}{18}$th or $\frac{1}{20}$th of what they would be if brass were used. A proof that the waste is almost entirely confined to the $C^2 r$ loss is afforded by the fact that a 75 kilowatt machine when driven on open circuit but excited to give its full voltage, only absorbs 3 H.P., the armature keeping quite cool. It is a curious point that in these machines the losses due to friction, hysteresis and parasitic currents, though moderately great at low loads, are not only proportionally but actually less at full load. Machines which show very great losses at low loads are uneconomical for central station work.

The construction of this alternator is more completely shown in Plate XIV., which depicts the machines erected in the Leicester central station. In its general features it is, as already seen, similar to the machines made by the Brush Company for some years, but with certain detail modifications. An end elevation, partly in section, is shown in Fig. (1); a side elevation in Fig. (2); a part section of the field-magnet—

to a larger scale—in Fig. (3); side and end views of an armature coil—to a larger scale—in Figs. (4) and (5). The armature is stationary, and consists of 120 coils mounted in ebonised German silver clamps—see Figs. (4) and (5)—secured to the armature ring by bolts passing through slotted holes in the flange of the ring—see Fig. (5). The armature coils consist of thin copper ribbon wound with suitable insulation round a slate core. Down the middle of the slate core a number of small slotted holes are drilled, these holes serving for a lacing of hard-tanned cord which is put round the coils under pressure after they have been covered with a thin layer of mica and tracing-cloth, the object of which is to prevent a sparking to the poles and to earth. They are set radially round a gun-metal ring, which is bolted to a cast-iron frame divided into four sections, two of which are below the floor level; each section is pivoted on end girders of cast iron, and can be readily swung back for inspection or repair of the coils. An equalizer is placed in one of the girders, as the two halves of the armature are connected in parallel. The field-magnet consists of massive steel castings with 60 pairs of polar projections, and is excited by one central coil provided with two gun-metal collecting rings mounted on the shaft, and the whole rotates in ample swivel bush bearings. An examination of the section of the magnet—seen in Fig. 3—will render description almost unnecessary. The field winding is an annular coil wound directly on the annular cast steel core, the winding being separated into two portions, leaving a radial space the whole way round. A number of conical radial air-passages allow a very free supply of air for ventilating and cooling purposes to pass from the hollow hub quite through the field winding, and over the armature which stands in the air-gap between the polar extensions. The magnet will be seen to consist of two cheeks secured by bolts and circular keys to the inner flanged magnet core. In smaller sizes of machines these cheeks are cast steel, each in one piece, but in the machine illustrated, and in all the larger machines, each cheek consists of two pieces, divided as shown. The armature ring is divided into four portions hinged at the ends of the machine near the horizontal diameter. This arrangement

allows of any one quadrant being readily withdrawn for purposes of examination, or cleaning, or repairing. In Fig. (1) is shown a quadrant standing out from the magnet in this way. The whole of the armature coils are accessible without removing any part of the machine, because there is a gap between the adjacent poles on either side, rather more than equal to the width of one armature coil. Thus, in any position, half the armature is accessible, and by moving the field-magnet round very slightly, the other half becomes accessible. This facilitates the ordinary cleaning work, while for periodical examination it is easy to withdraw the armature quadrants as shown. End play is limited by taking the thrust on a shoulder on the shaft bearing, on the inside end of each bearing. The lubrication is effected by means of a small oil pump of the Roots' blower type, seen in Figs. (1) and (2) at the side of the machine. These machines work at 96 revolutions per minute, having an output of 100 amperes at 2000 volts. The smallness of the armature reactions may be judged by the circumstance that if the excitation is kept constant, the voltage rise from full load to no load is only 7 per cent.

A number of Mordey alternators of 750 kilowatt output were constructed by the Brush Co. for the City of London lighting station.

Mr. Mordey has designed[1] a considerable number of alternative forms, all characterized by the combination of the two principles of simplicity of magnetic circuit and non-reversal of polarity in the armature. Some designs for machines of kindred type have been patented by W. Main.[2]

Parsons' Alternator.—This is a high-speed machine of bipolar or tetrapolar type designed for running at 3000 to 10,000

[1] Specification of Patent, 8262 of 1887.

[2] Specifications Nos. 15,858 and 16,032 of 1887. The device of employing field-magnets with a greater number of pole-pieces than of exciting coils had been previously employed by Holmes (Specification 2060 of 1868), and more recently by J. and E. Hopkinson. Another machine, by Klimenko, shown at Vienna in 1883, had a fixed armature with iron cores between the poles of a revolving field-magnet, with multiple pole-pieces.

revolutions per minute, when coupled to the special high-speed steam turbine[1] of the same inventor. Hence it is sometimes known as a *turbo-alternator*. This combination has lately come into notice owing to its possessing the qualities not only of a good efficiency, but of an almost complete freedom from mechanical vibrations. It has in consequence been adopted for city lighting stations in various parts of England. It occupies less space than any other form of combined plant.

Plate XV. gives a scale drawing of a 350 kilowatt turbo-alternator of the same design as those used by the Metropolitan Electric Supply Co. in their central station, Manchester Square, London. The armature consists of laminated iron, the core-disks measuring 18 inches outside diameter. There are 60 holes around the circumference, through 40 of which are passed conductors. Thus there are virtually only two coils, with 10 turns in each, and yet so great is the speed that a pressure of 1000 volts is generated. The machine having four poles, a speed of 3000 revolutions per minute gives a frequency of 100 per second. The governing of the machine is accomplished as follows. Steam is admitted to the turbine in a series of gusts by the periodic opening and closing of a double-beat lift-valve, the valve being opened once in every 15 revolutions. The duration of each gust is controlled by a solenoid which is connected as a shunt to the field-magnets. The field-magnets being excited by a small continuous-current machine on the same shaft as the alternator, the pressure at its terminals is a measure of the speed. The regulator, which will be seen in Plate XV. on the top of the magnets, operating a long lever reaching to the valve in question, has a series coil as well as a shunt coil, the effect of which is to increase the speed at heavy loads so as to keep the pressure constant. At full load the gusts become blended into an almost continuous blast, the lift-valve closing only momentarily or not at all. The action of this governor is most satisfactory. The consumption of steam is only 25 lbs. per kilowatt-hour at full load, and with super-

[1] See *Electrician*, xx. 103, 1887; and *Proc. Inst. Civil Engineers*, xcvii., Feb. 1889

heating it can be still further reduced. The total weight of this plant, including turbo-alternator, exciter and bed-plate, is about 12 tons. The copper in the armature weighs 58 lbs.

General Electric Co.'s Alternators.—The Thomson-Houston alternators with stationary external magnets and internal revolving armature were described in the previous edition of this work, where also an illustration was given of the "composite" method of excitation. These were high frequency machines of 133 cycles per second. Some of these alternators, of 500 kilowatt output at 100 periods per second, have recently been furnished to the City of London lighting station, where they are direct driven by Willans triple-expansion three-crank engines. The same company has lately developed a low-frequency alternator operating on an unsymmetrical 3-phase plan, termed the "monocyclic" system,[1] the third circuit being merely intended for starting motors.

Westinghouse Co.'s Alternators.—These have already been generally described. At the Chicago Exhibition in 1893 were shown some large 2-phase alternators. They resembled Fig. 402 in general design, but were virtually double machines, having side by side two similar field-magnets, each of 36 poles, and within two similar armatures upon the same shaft. But the armatures were "staggered"; that is to say, they were so mounted that one of them had an angular advance over the other equal to one-half the angular breadth from a N-pole to a S-pole. By merely shifting the second armature the same machine might be used as one single-phase alternator. In this case the adoption of a 2-phase system is not accompanied by any economy of space or material in the machine. These alternators are of 750 kilowatt output, running at 200 revolutions a minute, and having a frequency of 60 periods per second.

In its more recent polyphase machines[2] the Westinghouse Company has adopted a "distributive" winding (p. 581) of the armature. It also constructed the Niagara alternators described below (p. 636).

[1] *Electrical World*, xxv. 182; *l'Éclairage Électrique*, iii. 152.
[2] *Ib.* xxv. 713, 745, 1895.

Allgemeine Co.'s Alternators.—The *Allgemeine Elektricitäts-Gesellschaft* of Berlin has developed the 3-phase system in its alternators, from the designs of Mr. Dobrowolsky. Fig. 420 illustrates a Drehstrom generator of 89 kilowatts, with fixed external radial poles, and a revolving armature with sunk wave-winding.

FIG. 420.—ALLGEMEINE CO.'S 3-PHASE ALTERNATOR.

The large 3-phase inductor alternators made by this company for the Strassburg lighting station are considered later.

Oerlikon Co's. Alternators.—In 1890–91 this company constructed from the designs of Mr. C. E. L. Brown the 3-phase alternators for Lauffen on the Neckar. They were intended for supplying current to the town of Heilbronn, six miles away, but were first employed in the now famous historical transmission of power from Lauffen to Frankfort, a

distance of 110 miles, on the occasion of the Frankfort Exhibition. Though propelled by vertical-shaft turbines, the alternators have horizontal axes driven by toothed wheel gearing. They have revolving internal field-magnets with an external armature with zigzag arrangements of conductors passing through holes in the core-rings. Fig. 421 gives a general view, whilst Fig. 422 shows the field-magnet after the armature has been slid away for inspection. The machine generates three currents, each of 1400 amperes at a pressure of 50 volts; taking 300 horse-power when running at 150 revolutions per minute. The armature has an external diameter of 189·4 cm. (nearly 6 feet) and an internal diameter of 176·4. The total thickness of core-rings, parallel to the shaft, is 38·0 cm. Around the inner periphery of the core-

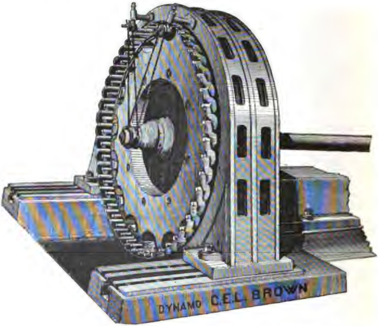


FIG. 421.—THREE-PHASE ALTERNATOR USED AT LAUFFEN.

rings are 96 circular holes 33 mm. in diameter at distances of 60 mm. apart. Each of these holes is lined with a tube of asbestos, and through each passes a solid copper rod 29 mm. in diameter. The core-rings, built up of segmental stampings, are assembled in a strong cast-iron frame. The winding, if such it can be called, is in three independent zigzags of 32 conductors each, connected according to the following scheme:—

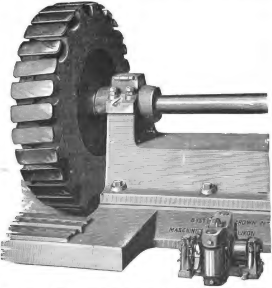


FIG. 422.—FIELD-MAGNET OF 3-PHASE ALTERNATOR AT LAUFFEN.

Set A, 1, 4, 7, 10, ... 91, 94.
Set B, 95, 92, 89, 86, ... 5, 2.
Set C, 93, 90, 87, ... 3, 96.

The ends of Nos. 94, 2, 96, are connected to a common junction J, while Nos. 1, 95 and 93 are severally brought out to three external terminals. This constitutes a star-winding

(p. 669); the general arrangement being illustrated in Fig. 423.

The gap-space between the armature core-ring and the pole-faces of the field-magnet is 6 mm. This field-magnet has 32 poles. It is of great solidity and simplicity, having but a single magnetic circuit. The exciting coil is wound in a channel on the periphery of a sort of pulley of cast iron, to which are bolted two steel rims, each carrying 16 polar expansions or horns. Each of the polar faces has an area of 36 × 16 sq. cm. The channel is 18 cm. wide and 9 cm. deep. In it lie 496 windings of copper wire 5 mm. diameter. A

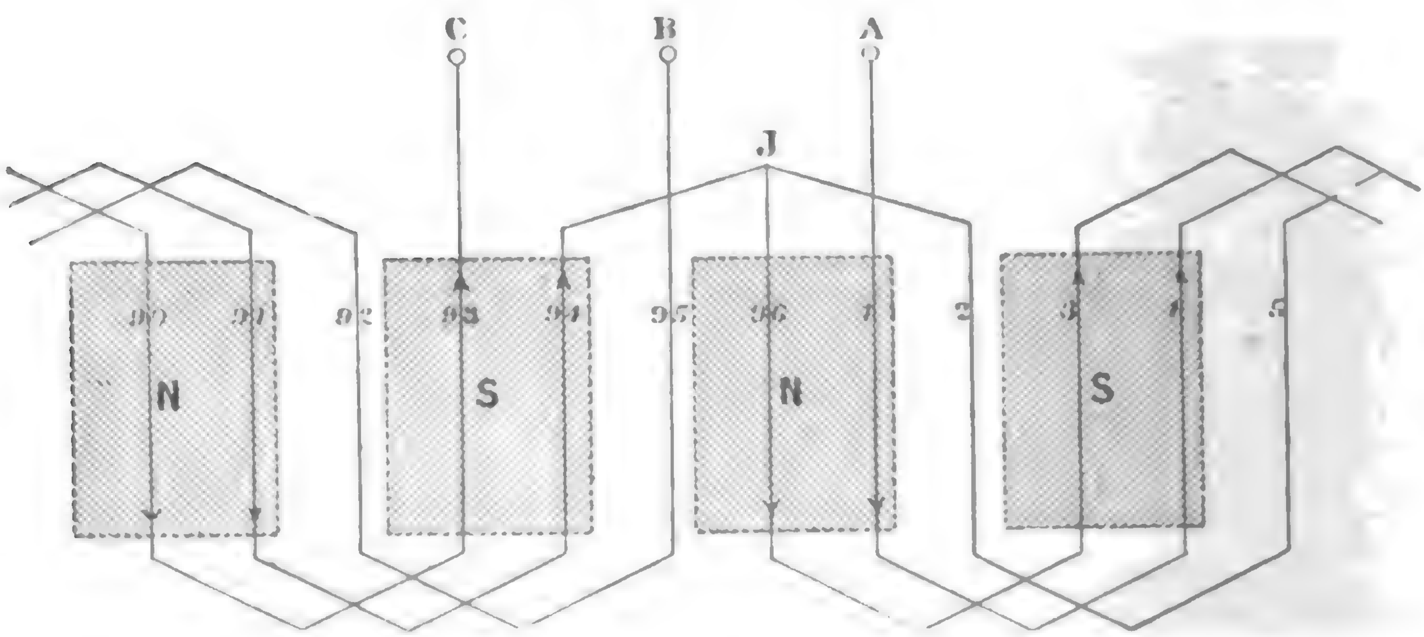


FIG. 423.—DEVELOPED DIAGRAM OF WINDING OF 3-PHASE ALTERNATOR.

section of this channel is given in Fig. 424; and Fig. 425 illustrates the way in which the polar horns project inwardly, the N-poles between the S-poles over the exciting coils. This arrangement reduces the cost of construction and of excitation to a minimum. In fact, on open circuit only 100 watts are spent on excitation—one-twentieth of one per cent. of the output; and at full load, when the armature reaction is a maximum, it is still far less than one per cent. This excitation is furnished by a small separate dynamo. The exciting current is conveyed to the rotating part by means of flexible metallic cords running over insulated pulleys, in lieu of the usual contact rings and brushes. At full speed and normal voltage,

the loss by friction and hysteresis is 3600 watts, or under 1·7 per cent. of the maximum output. The loss by resistance of armature windings at full load is 3500 watts, making the commercial efficiency over 95 per cent. The heating is, in the total absence of eddy-currents, quite negligible. The weight is 4½ tons. As there are 16 pole-pairs and the speed is 150 per minute, the frequency is 40 periods per second. The electromotive-force generated in each of the three windings, as measured between the common junction J and the outer terminal, could be increased up to 55 volts.

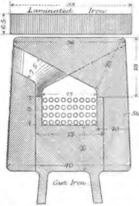


FIG. 424.—SECTION OF FIELD-MAGNET.

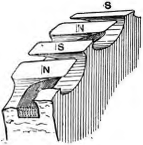


FIG. 425.—SKETCH OF FIELD-MAGNET.

The same design was repeated, with the difference that the shaft was set vertically over the turbines, in the three machines made by the Oerlikon Co. to convey power to their works from Hochfelden, 24 kilometres distant. They are depicted in Fig. 511.

A more recent 3-phase generator of the Oerlikon Co., shown in Fig. 426, has a revolving field-magnet of the same type as the preceding machines; but the armature is lap-wound, the coils passing through slots in the laminated external core. The exciter is carried on a bracket at the end

of the machine. This machine has an output of 22 amperes at 5000 volts, at 500 revolutions per minute, taking about 150 H.P.

Brown's Alternators.—Since 1891 Mr. C. E. L. Brown has continued to develope the vertical-shaft type of generator which he introduced when constructor to the Oerlikon Co. Fig. 427 gives a general view of an alternator of the "umbrella" type, with revolving internal field-magnets, hung upon a six-armed spider. The external core-rings have perforations as in Fig. 421, through which in low-voltage machines pass the stout copper conductors coupled up in zigzag very much as in Brown's continuous-current drum-armatures. The two-layer winding is excellent for this type of machine. In high-voltage machines the coils are wound in a lap-winding on plans resembling Fig. 405 or Fig. 406 according to circumstances. A large number of the machines are now in operation. One of these machines, a 3-phase generator, has for some years done excellent work at Schönenwerth near Aarau in Switzerland, furnishing current for motors in a large shoe

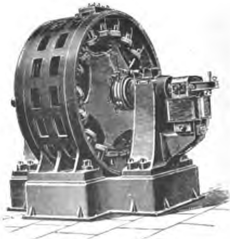


FIG. 426.—THREE-PHASE ALTERNATOR OF THE OERLIKON CO.

factory. More recently the town of Aarau has been provided with a central station which derives its power from the waters of the river Aar by means of turbines; the generators being of the same type.

To the Niagara Cataract Construction Company, Mr. Brown submitted two designs of "umbrella" type, with revolving field-magnets, for alternators of 5000 H.P. One of these designs is reproduced in Plate XVI., and shows the 2-layer winding in the stationary armature, together with the arrangements for lubrication.

In recent years various forms of polyphase alternators have been introduced by Messrs. Brown, Boveri & Co. Some of these machines present no special feature to distinguish them from ordinary alternators beyond having the coils of the armature arranged in sets of twos or threes to correspond to 2-phase or 3-phase work.

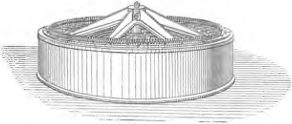


FIG. 427.—BROWN'S "UMBRELLA" TYPE OF ALTERNATOR.

Recently Mr. Brown has adopted a form of revolving field-magnet having a series of outward-pointing radial poles, with the peculiarity that only alternate poles are wound with exciting coils, the intermediate ones being simply projections of cast iron of larger cross section than the intermediate cylindrical cores that receive the coils. He finds that for operating motors it is needful to employ a field-magnet less subject to armature reactions than the form used in the Lauffen alternators. Fig. 428 shows one of his 2-phase alternators of 300 H.P., in which this system of field-magnet winding

is illustrated. The armature of this machine is of the same general construction as the stator of the 2-phase motor shown in Fig. 470, the only real difference between the two machines being that the one has a separately excited field-magnet, relatively to which the poles remain fixed, and the other has a rotor in which the poles change in position.

FIG. 428.—TWO-PHASE ALTERNATOR (225 KILOWATT).

For the central station at Frankfort, Mr. Brown designed the five 550 kilowatt alternators, driven at 85 revolutions per minute. In these machines (Fig. 429) the projecting poles of the revolving magnets are each separately wound, the excitation being derived from a continuous-current 4-pole machine on the end of the shaft. A point of novelty in the design is the construction of the stationary external armature

as a wheel capable of being slowly turned round so as to bring each part to a position convenient for inspection and cleaning.

Plate XVII. gives the drawings of a smaller alternator of

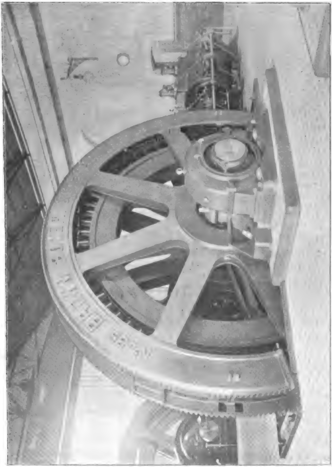


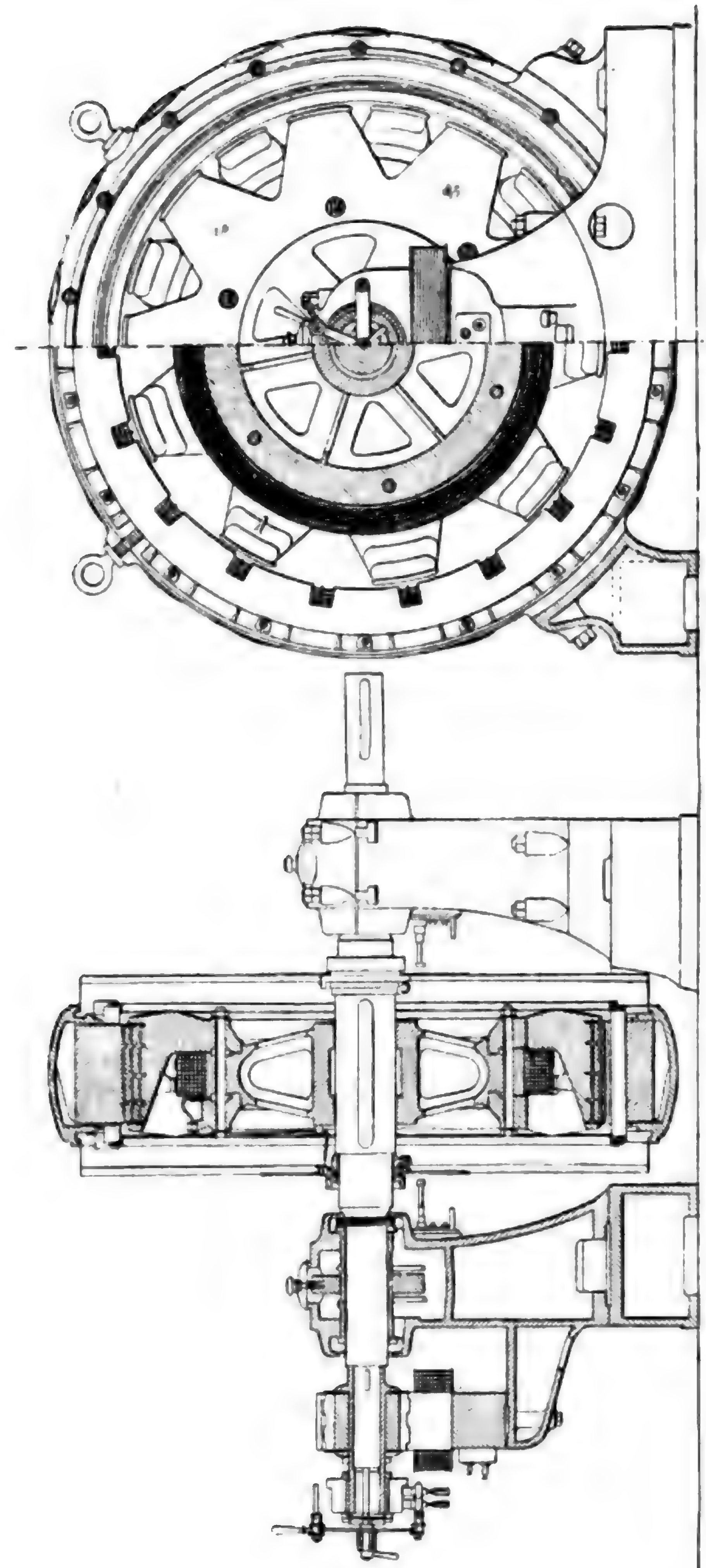
FIG. 429.—SINGLE-PHASE ALTERNATORS AT FRANKFORT.

similar design, in which can be seen the way in which the armature cores are constructed in hinged sections, allowing of being removed for cleaning or repairs.

Alioth Convertible Alternators.—Messrs. Alioth & Co. of Münchenstein near Bâle, have recently constructed several 4000 volt. 300 H.P. alternators for a power station at Neufchâtel, which are intended to be convertible at will, either into monophase or triphase machines. Fig. 430 gives a section of one of these machines parallel to the shaft, showing the exciter on the left and the detail of the self-oiling bearings. The field-magnet, as seen in Fig. 431, has nine pairs of poles and is of the same general construction as the field-magnets of the machines shown in Figs. 408 and 424. This magnet is interchangeable with one having six pairs of poles, in case the machine should be required as a 3-phaser. The crowns of poles are of mild cast steel with laminated faces. The armature coils, 18 in number, are wound on formers, and then slipped over the laminated iron projections. Connected in two sets of nine each they yield a monophase current, but when three sets of six are joined in star fashion the machine is a very efficient 3-phaser. The power station supplies both single-phase and 3-phase current, and it is convenient to have the machines convertible.

The Niagara Alternators.[1]—When the project of utilising the water-power of Niagara by turbines was taking shape, the Cataract Construction Company invited many different manufacturers in Europe and in America to submit plans. The machines were to be of 5000 horse-power, driven by turbines making 250 revolutions per minute. Many of these designs were extremely good; nevertheless it was determined to have the machines manufactured in America, owing to the high tariff charged on imported goods, and to the cost of transport. Some of the designs (including those of Mr. Brown) were of the "umbrella" type, but for various reasons (turning mainly upon the constructive difficulties arising from size and speed) Professor Forbes and Mr. Coleman Sellers were in-

[1] For an illustrated description of the works carried out, see *Cassier's Magazine* (N.Y.), July 1895. Figs. 432 and 433 are taken from the article by Mr. Stillwell.



FIGS. 430 and 431.—ALIOTH & CO.'S CONVERTIBLE ALTERNATORS.

structed in May 1893 to get out further plans for alternators of the proposed type. Professor Forbes fixed upon an externally-revolving umbrella field-magnet, with inwardly-pointing poles held together by an external annulus of steel, as possessing both great strength and a large fly-wheel action.

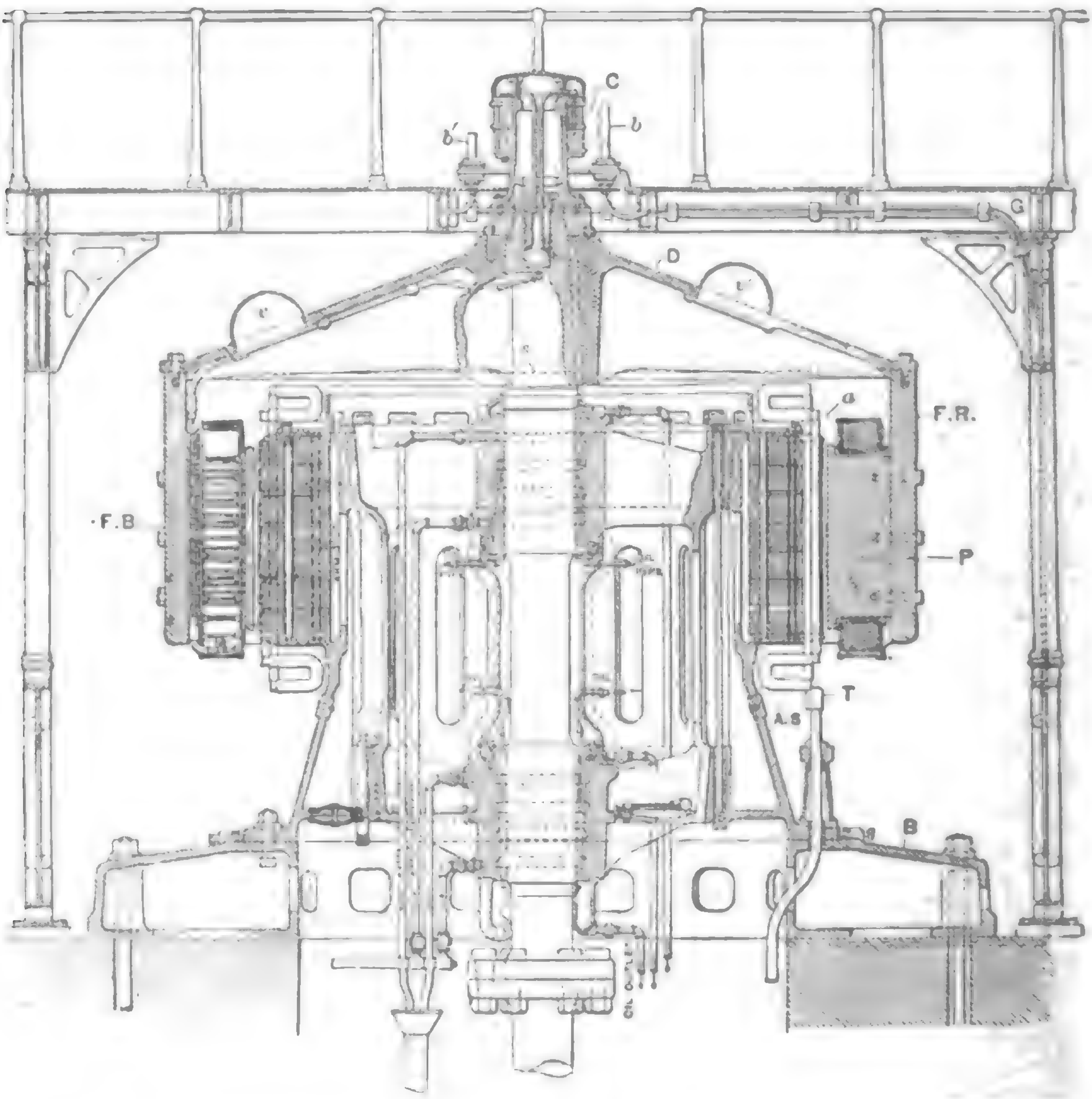


FIG. 432.—SECTIONAL ELEVATION OF NIAGARA 5000 H.P. 2-PHASE GENERATOR. Scale 1 : 50.

At first he prepared designs for a 2-phase machine, having the low frequency of $16\frac{2}{3}$ periods per second, with 8 poles. Eventually, after the Westinghouse Company had been selected as manufacturers, it was decided to fix the frequency at 25, and to wind the armatures for 2000 volts. The drawings

published by Professor Forbes[1] relate to the earlier design, and have certain complications about the armature which became unnecessary when it was decided to keep the voltage at 2000.

The machines as actually constructed are shown in Figs. 432 and 433. The field-magnet consists of a nickel-steel ring

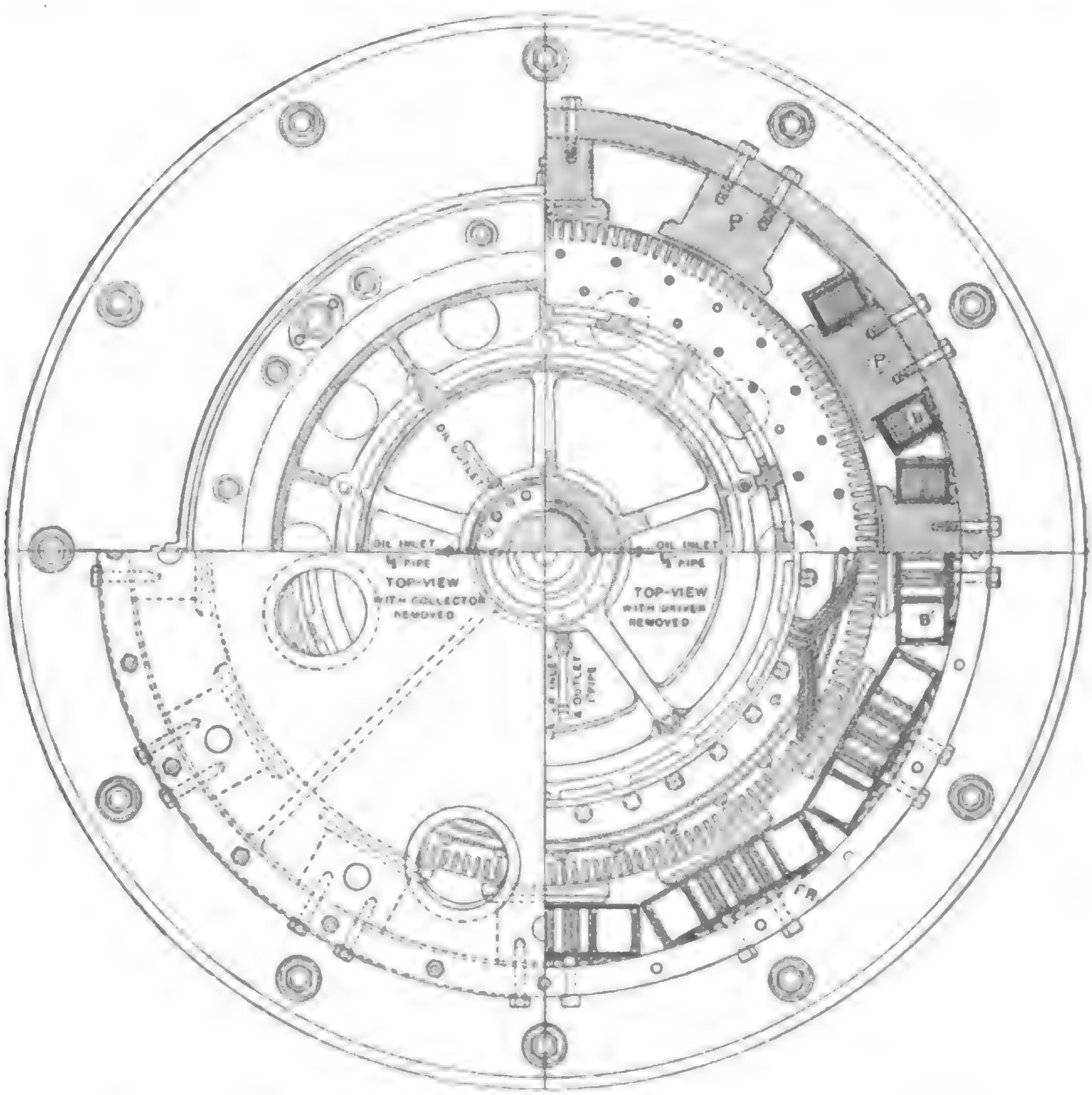


FIG. 433.—PLAN OF NIAGARA 5000 H.P. 2-PHASE GENERATOR.

forged without a weld, towards the interior of which project 12 pole-cores. This is supported by an umbrella-shaped driver fixed to the top of the shaft. There are 187 slots in the armature with two conductors in each slot. Each conductor

[1] *Journal Inst. Electrical Engineers*, Nov. 1893.

is $1\frac{11}{32}$ inches by $\frac{7}{16}$ in section, with slightly rounded edges. The method of connecting up is seen in the drawings, as also the method of bolting the laminated iron to the cast-iron frame of the armature. Around the hub of the bearings grooves are cut (shown in dotted lines) which permit water to circulate and keep the bearings cool.

CONSTANT-CURRENT ALTERNATORS.

A variety of alternators for supplying currents of an unvarying number of virtual amperes for the purpose of arc-lighting in series has been evolved in the United States ; the principal forms being those of Stanley[1] and of Heisler.[2] The principle of these machines is to so construct the armature that it has great self-induction. This is accomplished in the Stanley constant-current alternator by using in the armature a fine wire of many turns wound deep in nicks in the core-disks.

INDUCTOR ALTERNATORS.

In the inductor type of alternator none of the copper conductors move, the only moving parts being masses of iron whose motion sets up variations in the magnetic flux. This principle, suggested by several early workers (*see* Historical Notes, p. 11) was revived by the author of this treatise in 1883.[3] During the last two or three years much progress has been made in the application of machines of this type.

Kingdon's Inductor Alternator.—In this machine the inductor principle is applied in the following way. A ring having a large number of internally projecting poles is entirely built up of laminæ of soft iron. As shown in Fig. 434, the alternate poles A are wound with coils to serve as armature parts, whilst those between them F are wound with other

[1] *Electrical World*, xv. 45, and xvi. 339, 1890 ; also *The Electrician*, xxiv. 623, xxv. 145, and xxvi. 20, 1890.

[2] *Electrical Review*, xxv. 207, 1889.

[3] Specification of Patents, No. 1639 of 1883, which led up to Mr. Kingdon's form, see *Electrical Review*, xxii. 178, 1888.

coils to act as the magnet part. Upon an internal wheel are borne masses of laminated iron P, which in rotating produce rapid periodic reversals in the magnetic polarity of the cores of the armature parts, and set up alternate currents in the coils that surround them.

In the 50 kilowatt machine there are 16 field-magnet or primary coils, and 16 armature or secondary coils. The inductor wheel carries 16 inductor blocks, each just long enough to span the width of two successive coils on the poles of the outer ring. Its diameter is 4 feet 5 inches, and breadth 12 inches ; speed 350 revolutions per minute.

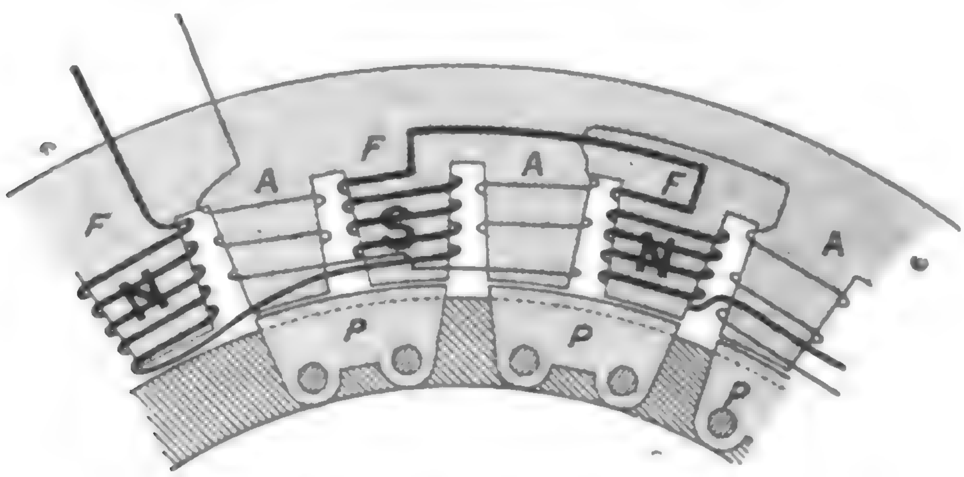


FIG. 434.—KINGDON'S INDUCTOR ALTERNATOR.

Mordey's Inductor Alternators.—In 1888, Mr. Mordey designed[1] several types of inductor machines, which were described in the previous edition of this work. In some of these machines there was but one primary winding, and in others both primary winding and secondary winding consisted of a single annular coil each, though the polar projections were numerous. These machines may be looked upon as an apparatus for periodically varying the mutual induction between two circuits in one of which there is a steady current.

Stanley-Kelly Inductor Alternators.—The Stanley-Kelly Co., of Pittsfield, Massachusetts, has brought to great perfection a 2-phase alternator, having rotating inductors of cast steel with laminated polar projections. The armature part closely resembles Fig. 477, which shows the stationary part of a Stanley-Kelly motor.

[1] Specification of Patent, No. 5162 of 1888.

Elihu Thomson's Inductor Alternator.—This machine was described and figured in the previous edition of this work. The inductor was a simple toothed wheel, built up of laminated disks mounted on a cylinder of iron.

FIG. 435.—PYKE AND HARRIS'S ALTERNATOR.

Pyke and Harris's Inductor Alternator.—This compact form, which has been very successful for small machines, is depicted in Fig. 435. The primary or magnetising coil is an

internal helix wound with its plane at right angles to the shaft, surrounding a central pole, and is surrounded by an external iron mantle. Two laminated rings with toothed projections support two sets of secondary or armature coils seen in the figure. On the shaft is fixed a revolving carrier which supports the laminated inductor masses. The solid part of the field-magnet acts also as a bearing. The 6-kilowatt machine runs at 740 revolutions per minute. It is 21 inches high, and weighs 350 kilogrammes.

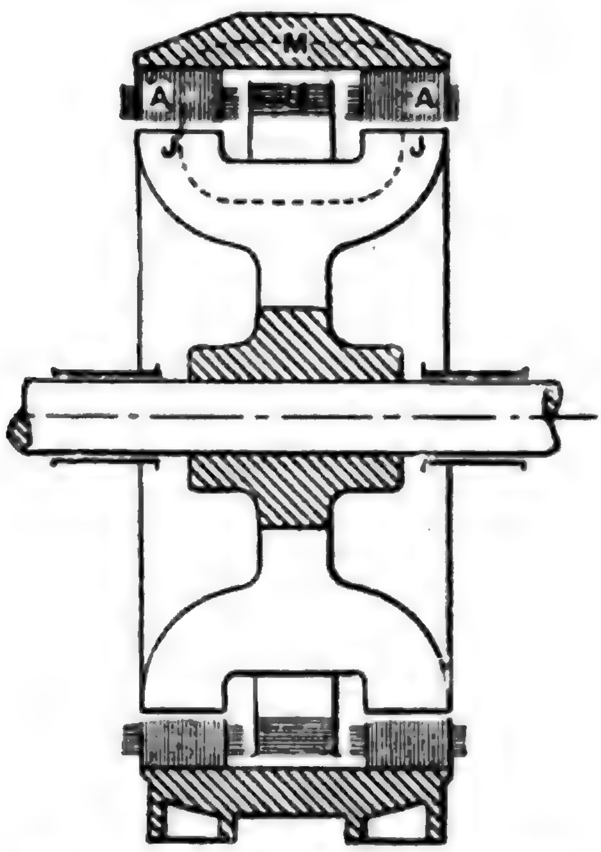


FIG. 436.—SECTION OF DOBROWOLSKY'S INDUCTOR ALTERNATOR.

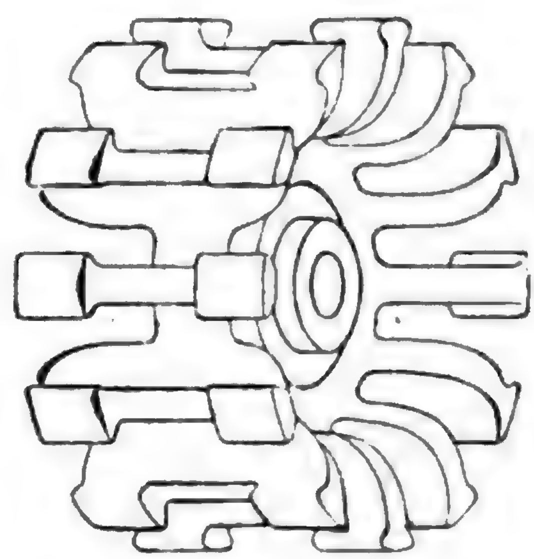


FIG. 437.—INDUCTOR OF DOBROWOLSKY'S ALTERNATOR.

Allgemeine Co.'s Inductor Alternators.—Two types of inductor machine have lately been constructed from the designs of Mr. Dobrowolsky.[1] The first, which closely resembles the Stanley-Kelly alternator, is represented in Figs. 436, 437 and 439. The magnetic circuit passes through an external iron case and two armature core-rings A A built up of stampings with teeth surrounded by coils, and is completed through the yokes J J of the revolving inductor, which is shown separately in Fig. 437. For 3-phase machines the teeth of the

[1] *Elektrotechnische Zeitschrift*, Feb. 7, 1895; see also *Electrician*, xxxv. 91.

fixed armature part are three times as numerous as those of the inductor, as shown in Fig. 438; but pierced core-rings

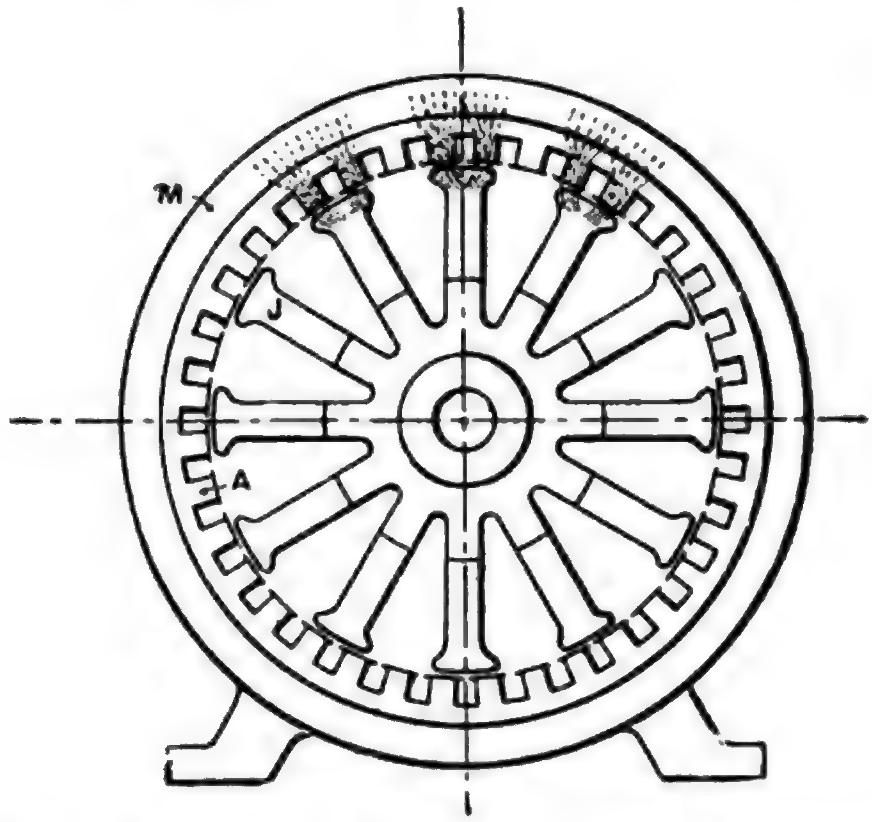


FIG. 438—END-VIEW OF 3-PHASE INDUCTOR ALTERNATOR.

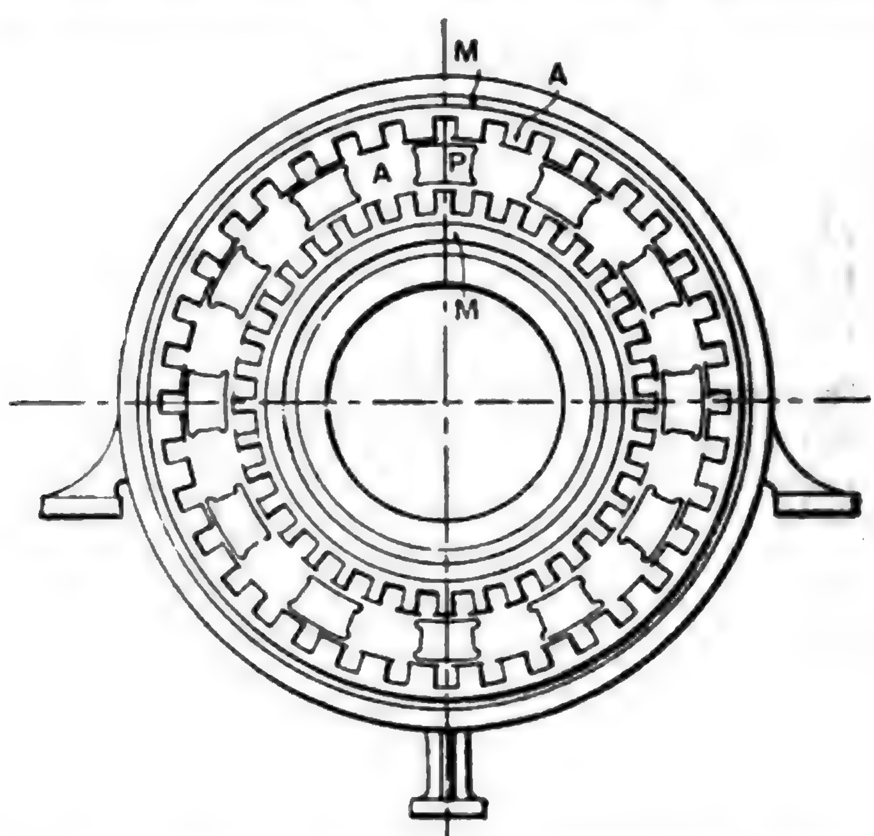


FIG. 439.—THREE-PHASE INDUCTOR ALTERNATOR AT STRASSBURG.

like Fig. 406 may be used. The large 280 kilowatt alternators built by the Allgemeine Co. for the central station at

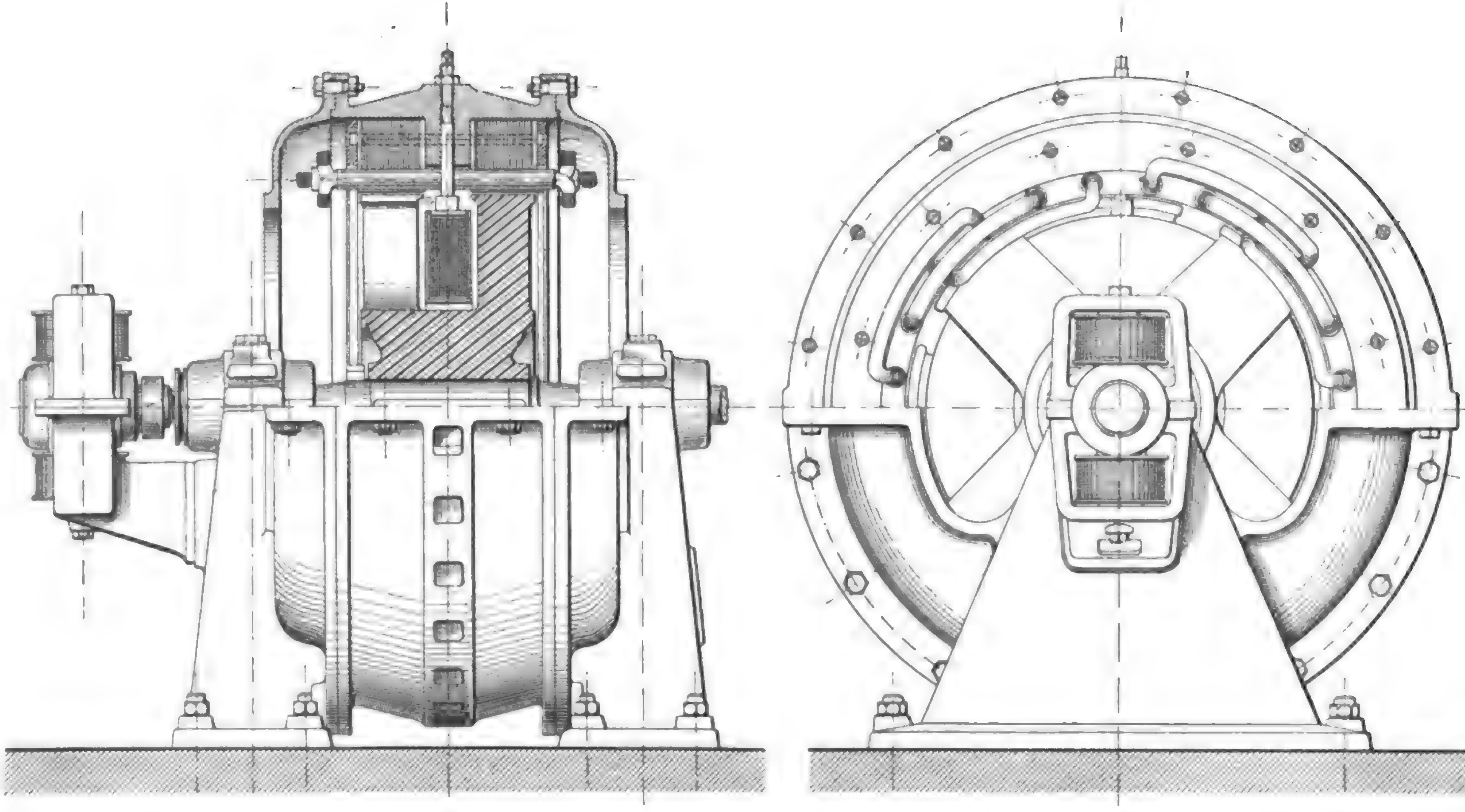


FIG. 440.—BROWN'S 3-PHASE INDUCTOR GENERATOR, 150 H.P., 600 REVS. 5300 VOLTS. Scale 1 : 20.

Strassburg, are of the same type as the Pyke and Harris machines, having laminated inductor masses P, Fig. 439, revolving between two armature core-rings. Their speed is 150 revolutions per minute. The excitation is 1·4 per cent. of the output; the armature resistance loss is 2 per cent., and total hysteresis loss is 1·3 per cent. The copper used is only 2 kilogrammes per horse-power, and the iron, excluding shaft and bearings, about 22 kilogrammes per horse-power.

Brown's 3-Phase Inductor Generator.—This is a machine constructed to meet the requirements of high speed with low frequency. The inductor magnet is simply a mass of cast steel having on each end a set of 4 arms, which, by the magnetizing action of a stationary coil between them, acquire opposite polarities. As shown in Fig. 440, these arms are set to operate alternately upon the coils of the fixed armature, which has its windings carried through holes in the inner periphery of two sets of core-disks mounted in an outer iron frame.

Other Inductor Machines.—Amongst other designs of inductor types may be mentioned those of Mr. Rankine Kennedy and M. Thury. The largest of Thury's alternators, which are built by the Compagnie de l'Industrie électrique, of Geneva, are those at Chèvres, six kilometres from Geneva, where the water-power of the Rhone is used for the lighting of that city. These machines, which are of about 900 kilowatts each, are two-phase machines with vertical shaft.

The reason of the tendency which manifests itself just now to favour the inductor type of alternator is not very apparent. Against the advantage that there is no moving copper, must be set the disadvantage of greater iron losses. In general, the efficiency of these machines is two or three per cent. lower than that of alternators of other types. They have, however, some constructional advantages in those cases where either an exceptionally high speed or an exceptionally low speed is a necessity.

CHAPTER XXIV.

THE COUPLING OF ALTERNATORS. SYNCHRONOUS MOTORS.

IF two alternate-current machines are joined up in the same circuit as in Fig. 441, they are in parallel when considered as forming part of the lamp circuit, and might be both supplying current to the lamps, but they are in series with one another if we consider the alternator circuit only, for we might cut the lamp circuit out altogether and A_1 might drive A_2 as a motor. Many of the considerations which govern the running of two machines as generator and motor govern the running of two machines in parallel. We shall, therefore, up to a certain point treat the two cases together, and in doing so consider the alternator circuit only, taking a certain direction round the circuit, viz. clockwise in Fig. 441, as the positive direction of electromotive-force and current. We may as well emphasize here the importance in all alternate-current problems of clearly stating what is meant by the positive and negative sense of the quantities considered, as the utmost ambiguity and confusion arises in many important contributions to the subject owing to the neglect of this precaution.

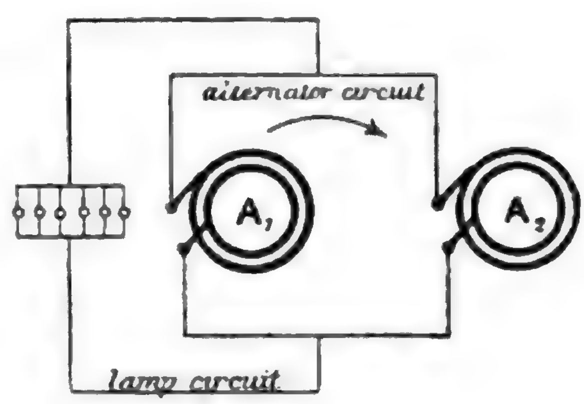


FIG. 441.

The simplest conception of two alternate-current machines in series is that of a closed conductor *a b c d*, Fig. 442, near different points of which two magnets rotate so as to cause it to cut their lines. The part *a b* may be considered as the

middle conductor of an alternator coil. The change of position of the field-magnet of an alternator with regard to the centre conductor of one of its coils is represented by the angle θ in Fig. 442. All the phase relations of the magnet's position, the electromotive-force, and the current, can be seen from this figure; and the full theory (so far as at present known) of the synchronous motor can be deduced from it by the aid of a few graphic diagrams.

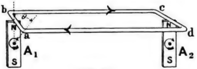


FIG. 442.

First of all consider that the magnet A_1 only is rotating. The electromotive-force e_1 induced by it, we will say, varies according to the law

$$e_1 = E_1 \cos \theta,$$

and may be represented by the projection upon a vertical line of the line O E_1, drawn to scale to represent the maximum electromotive-force E_1 and which is supposed to rotate clockwise about O in Fig. 443. If the self-induction of the whole circuit is L and the resistance R, we would have from previous considerations (see p. 562) the current lagging by the angle ϕ; the vertical projection of R C at any moment representing the electromotive-force which is in phase with it. Observe that a line drawn above the axis of X represents a positive electromotive-force or current, that is, an electromotive-force or current round the circuit in the direction indicated by the big arrow-heads in Fig. 442. The alternating current flowing along *c d* would tend alternately to turn the magnet A_2 clockwise and counter-clockwise so that it would not start, but if we artificially run it up to the speed of A_1 it will, under suitable conditions, keep on running in synchronism with A_1 and exercise considerable torque. These conditions we have to consider. Let us say that at a certain instant the magnets are in the position shown in Fig. 442. The electromotive-force generated in *c d* will be negative in sense and its magnitude

will depend on the strength of the magnet A_2. Suppose in the first place that the two magnets A_1 and A_2 are of the same strength, then the electromotive-force which each will induce in the circuit will be represented by the lines $\overline{O E_1}$ and $\overline{O E_2}$ in Fig. 444 ($\overline{O E_2}$ at the moment we are considering being negative). The two E.M.F.'s being equal and opposite, the resultant E.M.F. in the circuit will be zero, and there being no current to drive A_2 the friction of its bearings will slow it down so that it gets behind A_1 in phase. The electromotive-forces may then be represented by $O E_1$ and $\overline{O E_2}$ in Fig. 445, and the resultant electromotive-force will be $O E_3$. The phase of the current will depend upon the self-induction of the circuit. If there were no self-induction in the circuit the current would be in phase with $\overline{O E_3}$ and its magnitude would be $\frac{O E_3}{R}$.

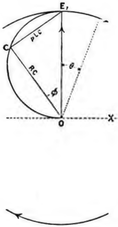


FIG. 443.

FIG. 444.

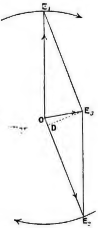


FIG. 445.

Now we have seen (p. 571) that when a current from an alternator differs in phase from the E.M.F. by less than 90°

the alternator is acting as generator and requires a force to drive it. If, on the other hand, the difference in phase between the current and E.M.F. is more than 90° (viz. between 90° and 270°) the machine acts as a motor and yields a torque. In Fig. 445 the difference in phase between $\overline{O\,E_3}$ and the electromotive-forces of both A_1 and A_2 is less than 90°, so that both machines will act as generators, and A_2 having no torque to drive it will stop. If, however, there be considerable self-induction in the circuit so that the current lags behind the

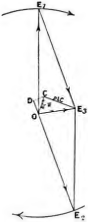


FIG. 446.

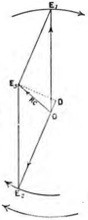


FIG. 447.

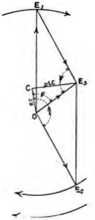


FIG. 448.

resultant $O\,E_3$ as shown in Fig. 446, where the line R C represents the phase of the current, then as the angle between it and $\overline{O\,E_2}$ is greater than a right angle, the machine A_2 will act as a motor. If we let fall the perpendicular C D upon the direction of $\overline{E_1\,O}$ we obtain line $\overline{O\,D}$, which divided by the resistance represents the component of the current which is in direct opposition of phase to $O\,E_2$, that is, the part of the current which is operative in driving A_2 as a motor. The power developed by A_2 is proportional to the product

$\overline{OD} \cdot \overline{OE_2}$. As the lines in the figure represent the maximum values of the E.M.F. and current, the power is equal to $\frac{OD_2 \cdot OE_2}{2R}$ (see p. 567). The magnet of A_2 would be displaced behind the magnet of A_1 just so much as to cause O D to be sufficiently great to exert the required torque.

So far we have considered the E.M.F. of the machines as equal. If we excite the magnet A_1 until it is stronger than A_2, so that E_1 is greater than E_2, then we may represent the state of affairs in Figs. 447 and 448. Fig. 447 shows what would happen if the self-induction were small as compared with the resistance.[1] The resultant E_3, and therefore the current, is more than $90°$ out of phase with E_2, a great torque results which makes the magnet of A_2 go faster than A_1 until it gets just so far in advance of it that O D is diminished to an amount which will give the required torque and no more. Thus we see that the effect of having the motor under-excited is to make its magnet lead in phase, while the effect of self-induction is to make it lag. If there is considerable self-induction in the circuit (as is usually the case, particularly with alternators with iron in the armatures), the phase relations of the various E.M.F.'s are those shown in Fig. 448. This may be taken as representing the most usual case of transmission of power by means of a synchronous motor; the effect of the self-induction in the circuit is to enable the motor to yield considerable torque whether its magnet is under or over-excited. Let us consider more exactly what happens when the excitation of field-magnet of the motor is varied, the load on the motor remaining constant. We see from Fig. 448 that $O E_2 = E_1 E_3$, so that we may take $E_1 E_3$ to represent the E.M.F. of the motor, that is to say, the counter E.M.F. or "back" E.M.F., as it is usually called. We may then draw the half-figure on a larger scale (see Fig. 449), and consider what happens when $E_1 E_3$ is varied in magnitude, while the impressed volts $O E_1$, the

[1] See Bedell and Ryan, "Action of a Single-phase Synchronous Motor," *Amer. Inst. Electr. Eng.*, March 1895, p. 197.

resistance R, the self-induction L, and the power of the motor P, all remain constant. R and L being known, ϕ, the angle of lag of the current behind the resultant E.M.F. $\overline{O\,E_3}$ is ascertained $\left(\text{for } \tan \phi = \frac{p\,L}{R}\right)$ and remains constant. Produce $\overline{O\,C}$ to F, and upon $\overline{O\,E_1}$, as diameter, describe the circle E_1 F O having the centre G. Join $\overline{F\,E_1}$, then E_1 F O being a right angle, O F is the projection of the impressed volts O E_1 upon the direction of the current $\overline{O\,C}$, so that $\frac{O\,F}{\sqrt{2}}$ gives the value of the virtual volts which are in phase with the current, whose virtual value is $\frac{C\,O}{\sqrt{2}\,R}$. The power yielded by the generator A_1 is therefore $\frac{O\,F\,.\,C\,O}{2\,R}$. Similarly $\overline{F\,C}$ being the projection of $\overline{E_1\,E_2}$, the power yielded by the motor A_2 is $\frac{F\,C\,.\,C\,\overline{O}}{2\,R}$, and this we are taking as constant. Now when the line $\overline{E_1\,E_3}$ alters in length the figure becomes changed in shape, but always in such a manner that the angle E_1 F O remains a right angle, so that F moves on the circle E_1 F O. At the same time the point C must move[1] on a circle C J H concentric with circle E_1 F O, in order that F C . C O (or J O . C O) may remain constant. Now, if C moves on the circle C J H the point E_3 must also move on a

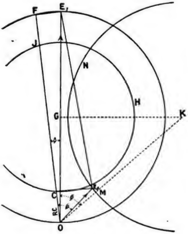


FIG. 449.

---

[1] R. V. Picou, "Transmission de Force par Moteurs alternatifs synchrones," *Bull. Soc. Int. Électriciens*, Feb. 1895.

circle, because ϕ remains constant and $\overline{OC}$ and $\overline{OE_3}$ bear to each other a constant ratio. The centre of the circle $M E_3 N$ which forms the locus of E_3, will be found by drawing $\overline{OK}$, making the angle ϕ with $\overline{E_1 O}$ and drawing $\overline{GK}$ at right angles to $E_1 O$. We are now able to find the value of any of the quantities represented in the figure for any given value of $\overline{E_1 E_3}$, the back E.M.F. of the motor. It may be pointed out that though $\overline{OE_1}$ has been taken to represent the electromotive-force induced in the conductors of the generator, all the above clock diagrams are equally applicable to the case where $\overline{OE_1}$ represents the electromotive-force of the line at the terminals of the motor; but then R and L represent the resistance and self-induction of the motor only. We see that in the figure as drawn the current lags behind the impressed volts $E_1 O$ by the angle β. If we decrease $\overline{E_1 E_3}$ we see that β will increase and R C will also increase. That is to say, if we decrease the excitation of the motor, the lag of the current behind the impressed volts increases and the current increases. If, on the other hand, we increase the excitation, we see from the figure that as E_3 moves up to M the angle β decreases to zero, the current being then at a minimum.[1] A further increase of the back E.M.F. of the motor will cause the current to increase, but instead of lagging behind the impressed volts it leads, the motor in fact acting as though it were a condenser placed in the circuit. If we plot a curve with the values of the back E.M.F. of the motor (or the exciting current when that is proportional), as abscissæ and the armature current as ordinates, we get a V-shaped curve showing the decrease of the armature current to a certain minimum, and its increase again as the back E.M.F. is augmented.

Mr. Mordey[2] obtained from a 50 kilowatt alternator running as an unloaded motor, the curve shown in Fig. 450. The values of the current in the motor field-magnet are

[1] Blondel, "Couplages et Synchronisation des Alternateurs," *La Lumière Électrique*, 1892, xlv. 423–563.

[2] "On Testing and Working of Alternators," *Inst. Elec. Engs.*, Feb. 1893.

taken as abscissæ, and the current in the armatures as ordinates.

Messrs. Bedell and Ryan[1] have given a similar curve for a small Westinghouse alternator, together with full particulars as to the E.M.F.'s of generator and motor and angles of lag, and have worked out clock diagrams for different points on the curve, showing that the theory agrees with what is found to occur in practice.

This property of an over-excited synchronous motor of causing the current to be in advance of the impressed E.M.F. would enable such machines to be used to counteract the tendency of the current to lag when transformers are in circuit, and thus to increase the power-factor of the line.

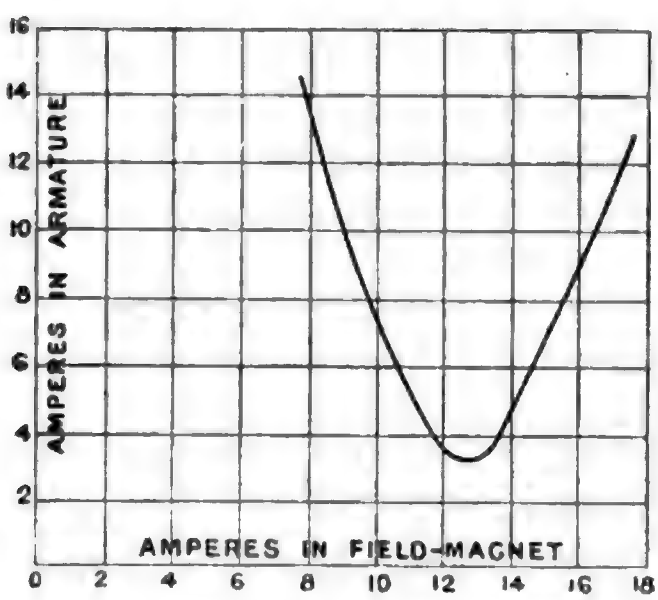


Fig. 450.

One of the bad effects produced by a current lagging behind the E.M.F. of the generator, is the demagnetizing action of such a current upon the field-magnet (see p. 596). It will be seen from Fig. 442 that so long as the current is in phase with the volts it has no demagnetizing effect, for when the current is at its maximum the magnet pole is directly in front of the conductor, as in A_1 in Fig. 442. An instant before the pole comes to this position, the armature current is helping the magnetizing current, and an instant afterwards it is opposing it, so upon the whole the mean strength of the magnet is not affected, though the maximum E.M.F. in the armature probably occurs a little sooner than it otherwise would do. If, however, the current lags, the maximum current flows just after the pole has passed the middle position, thus producing a strong demagnetizing

[1] "Action of a Single-phase Synchronous Motor," *Journal of the Franklin Institute*, March 1895.

action and a consequent fall in the volts unless the excitation of the field-magnets is augmented. If, however, the current leads, the maximum occurs when the pole is approaching the conductor, increasing the magnetization, and thus the volts are raised. A generator and motor being in opposition of phase, a current that lags with regard to the one leads with regard to the other; thus on switching in an under-excited synchronous motor to a generator whose current lags, there is a tendency for the generator volts to fall and the motor volts to rise. On gradually increasing the excitation of the motor the generator volts will rise, owing to the advance of the phase of the current. This is very clearly shown in the paper of Messrs. Bedell and Ryan before referred to (p. 654).

R. V. Picou has pointed out that in applying the construction given in Fig. 449 to the working out of a practical case, the lines $\overline{O E_1}$ and $E_1 E_3$ representing several thousand volts are so great, relatively to $O E_3$, that the arcs of the circles $E_1 F O$ and $C H J$ may be considered as straight lines, and $\overline{O E_1}$ and $\overline{E_1 E_3}$ as parallel. The construction is then simplified, [redacted] there is no difficulty in working to scale. An example is worked out in M. Picou's paper referred to above (p. 652).

There are several interesting deductions to be made from the graphic construction given above. Obviously the most economic condition for ordinary power transmission is to have the excitation of the motor such that the current is in phase with the impressed volts. Referring to Fig. 449, let us fix the condition that $R C$ shall be in line with $\overline{O E_1}$ and draw our diagram as in Fig. 451, setting off the line $O Z$, making the angle ϕ with $\overline{E_1 O}$. For any given load on the motor there is one particular value of current which will satisfy the prescribed

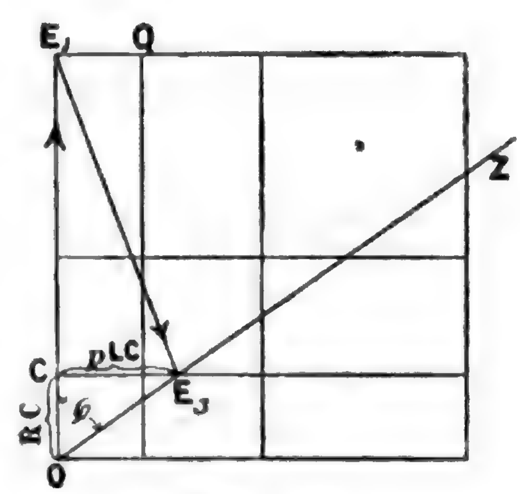


FIG. 451.

condition, and the line $\overline{\text{C O}}$ which represents R C will have to be set off at such a length, that $\frac{\text{E C . C O}}{2\text{ R}}$ is equal to the given power (see p. 652). Then drawing C E_3 at right angles to cut $\overline{\text{O Z}}$, $\text{E}_1\,\text{E}_3$ will represent the back E.M.F. of the motor in magnitude and phase. Now if we vary the power C will move along $\overline{\text{O E}_1}$ and E_3 will move along $\overline{\text{O Z}}$, the power yielded by the motor being always equal to the area of the rectangle C Q divided by 2 R, and that supplied by the generator equal to the area of the rectangle O Q divided by 2 R. When the power is zero $\overline{\text{E}_1\,\text{E}_3} = \overline{\text{E}_1\,\text{O}}$, the current being zero. The maximum power occurs when C Q is a square. From the figure we see that then

$$\text{max. power} = \frac{\text{E}_1^2}{4\text{ R}},$$

R C being equal to $\frac{1}{2}$ E_1 and the efficiency being 50 per cent. Thus we see Jacobi's law of the continuous-current motor, and the construction given on p. 496, are equally applicable to the alternate-current synchronous motor. The back E.M.F. of the motor for any prescribed power can be found readily from the figure (see p. 655, line 20).

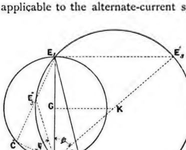


FIG. 452.

We can also get a very simple figure by which to study the changes in the back E.M.F. and current when the power is zero. The clock diagram for this case is given in Fig. 452, where R C is at right angles to $\text{E}_1\,\text{E}_3$, because if the power is zero the current must be at right angles in phase to

the back E.M.F. of the motor. As we change the value of $E_1 E_3$, the locus of the point C must therefore be the circle $O C E_1$; and from the reasoning on p. 652, the locus of E_3 must also be a circle whose centre is at K.

If we plot a curve taking on a convenient scale the back E.M.F. as abscissæ and the armature current as ordinates we find it is in the form shown by the thick line in Fig. 453. Beginning with E_3 coinciding with O we get the corner point C_0 in Fig. 453. As we increase the back E.M.F. passing counter-clockwise round the circle $O E_3 E_1$ in Fig. 452, the current increases until we reach the point E'_3 when it attains its maximum. R C is then equal to E_1, therefore the current $C = \frac{E_1}{R}$. If the motor were standing at rest the current through the armature would only be $\frac{E_1}{\text{impedance}}$, but if the motor is running light the back E.M.F. might be so adjusted in magnitude and phase as to completely balance the self-induction of the armature, so that a current would flow through it equal to $\frac{E_1}{R}$. In practice the upper portions of the curve in Fig. 453 would be difficult to realise unless the motor were constrained to keep in the proper phase relations, but theoretically we can follow E_3 round its circle until it coincides with E_1.

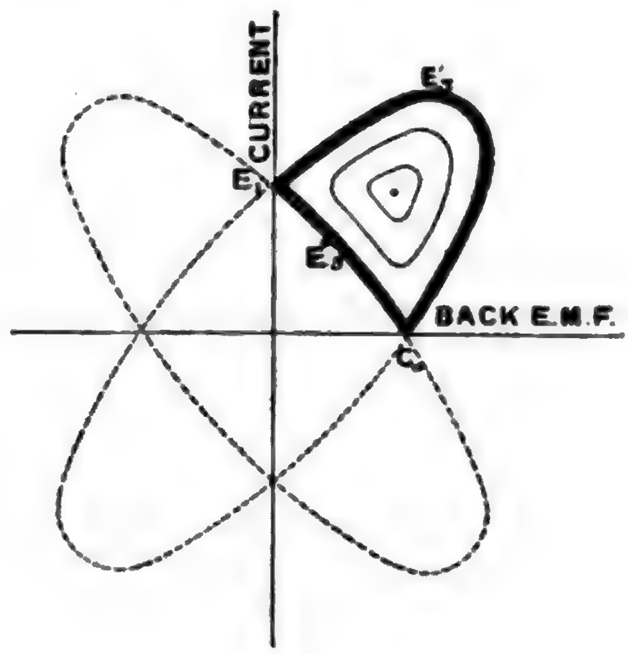


FIG. 453.

This curve $C_0 E'_3 E_1$ in Fig. 453, really forms part of an ellipse shown in dotted line, the equation to which is given below. If we follow E_3 further round its circle in Fig. 452 we find it passes through the point E_1; a question then arises as to whether we will give the positive or negative sign to the back E.M.F. in plotting the curve in Fig. 453.

The back E.M.F. having passed through zero would theoretically be negative, which would take us along the dotted ellipse, but if we still choose to call our back E.M.F. positive then our curve is the thick line $E_1 C_0$. This forms part of another ellipse similar to the first, that lies with its major axis sloping the other way as shown in the figure. If instead of plotting the back E.M.F. and current from Fig. 452, where the power is zero, we plot them from a clock diagram like that in Fig. 449, where the power has a fixed value, we would get curves like those shown by the fine lines in Fig. 453, the area enclosed by the curve becoming smaller and smaller as the power is increased, until at maximum power there is only one point representing current $= \frac{E_1}{2R}$ and back E.M.F. $= \frac{E_1 \sqrt{R^2 + p^2 L^2}}{2R}$. It is the lower corners of these curves that form the V-shaped curves referred to on p. 654. The equation to these curves is very simply deduced; for remembering that, in Fig. 448, the lines $\overline{OE_1}$, $\overline{E_1 E_3}$, $\overline{OE_3}$ represent respectively the electromotive-forces E_1, E_2 and IC, where I, the impedance, $= \sqrt{R^2 + p^2 L^2}$ we have

$$E_1^2 = E_2^2 + I^2 C^2 + 2 E_1 . IC . \cos \psi \qquad (1)$$

and $\cos \psi = \cos(\phi - \eta) = \cos \phi \cos \eta + \sin \phi \sin \eta$. Further we know

$$\cos \phi = \frac{R}{I}, \qquad \sin \phi = \frac{pL}{I};$$

$$\cos \eta = \frac{P}{E_2 C}, \qquad \sin \eta = \sqrt{1 - \left(\frac{P}{E_2 C}\right)^2},$$

where P = power of motor.

Substituting these values in (1) we get

$$E_1^2 - E_2^2 - I^2 C^2 - 2RP = 2pL \sqrt{C^2 E_2^2 - P^2},$$

which is the fundamental equation of the synchronous motor.[1] Taking E_2 and C as the only variables we obtain a curve like those in Fig. 453 for each value of P.

Parallel Running of Alternators.

It is found very convenient in central lighting stations to be able to run alternators in parallel, so that the machines may feed into one set of omnibus bars, and their number be altered at will to suit the load on the station, instead of assigning different parts of the town circuits to separate machines.

The principles which govern parallel running have been considered in Fig. 446. $\overline{OE_1}$ may be taken to represent the volts between the omnibus bars. The machine to be thrown in in parallel is run up to speed and its excitation is adjusted until its volts $\overline{OE_2}$ are equal to $\overline{OE_1}$. It has, before being switched in, to be *synchronized*, that is to say, it must not only be run at the same speed but the impulses of its electromotive-force must be got into step with those of the omnibus bars. To do this a synchronizer is employed. Fig. 454 illustrates the principle of one form of synchronizer. An incandescent lamp is fed from two transformers in series with one another: the primary of one transformer is connected with the omnibus bars, and that of the other to the alternator to be synchronized. The connexions are so made that when the machines are in synchronism the secondaries of the transformers assist each other in lighting the lamp. When not in synchronism they are in opposition. If the alternator to be thrown in is not going at the right speed it gets into and out of step alternately and the lamp blinks rapidly. The supply of steam is then altered to correct the speed, and the lamp is seen to blink more and more slowly until it takes several seconds between the instant of perfect darkness and the instant of full incandescence.

[1] Steinmetz, "Theory of the Synchronous Motor," *Amer. Inst. Elec. Engs.*, Oct. 1894; Rhodes, "A Theory of the Synchronous Motor," *Proc. Physical Soc.*, April 26, 1895, *Phil. Mag.*, July 1895. Also "Alternate Current Motors," *Elec. Review*, 1895, xxxvii. 182, 222.

Just at the moment of full incandescence, and when the voltmeter (see Fig. 454) indicates the full pressure, the switches are closed and the lamp forthwith shines without fluctuation, showing that the volts of machine are in step with the volts of omnibus bars. If the supply of steam is now increased the alternator will take up a portion of the load. The amount of current it will supply depends entirely on the amount of steam admitted to drive it. If the steam were cut off it would run as a motor and drive the engine. Fig. 446 does not show the main current supplied to the outside circuit, it only shows the resultant electromotive-force $\overline{OE_3}$ round the alternator circuit (see Fig. 441) which comes into existence in case A_2 should lag a little. This resultant electromotive-force produces a current which by reason of the self-induction of the circuit is out of phase by more than 90° with the lagging machine, and which therefore supplies power to it and hurries it up. It will be seen from the figure that the current represented by O D is greatest (for a given lag of the machine) when the angle ϕ is 45 degrees; that is to say, when in the alternator circuit R is equal to p L. In well-designed machines R and L are both kept as small as possible. It is sufficient if R is something of the order of p L.

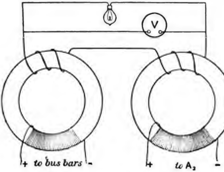


FIG. 454.

Synchronous Polyphase Motors.—A polyphase system of

distribution, while giving great facility in the use of self-starting motors, does not sacrifice the possibility of installing synchronous motors in cases where perfect uniformity of speed is desired. A synchronous motor for a polyphase system may consist of an ordinary alternator placed across two of the mains; but preferably it is identical in construction to the polyphase generators, and connected to all the lines. It differs from an asychronous motor mainly in the fact that instead of a rotor (Fig. 460) it has a field-magnet separately excited by means of a continuous current; and as the poles always keep the same position relatively to the iron of the magnet when once they are run up to the speed of the revolving poles of the armature, the respective poles take hold of each other and the magnet is dragged round in perfect synchronism. The ordinary single-phase synchronous motor, as we have seen, must be run up to speed by some independent source of power; but in a polyphase system the rotatory field acting upon conductors sunk in the pole pieces of field-magnets is sufficient to start the motor. It is thus possible to so far combine the principle of a polyphase asynchronous motor with a truly synchronous motor, that it shall be capable of starting itself, and after running up to speed, will keep its speed at all loads as constant as the periodicity of the supply. It is to be noted that while a polyphase generator will always act as a synchronous motor, it is not necessarily self-starting. Its design should facilitate the generation of currents in the polar projections if it is intended to be self-starting. A very good instance of an installation of synchronous motors of this kind is at the Ponemah Cotton Mills, Taftville, Conn., U.S.A.[1] Six hundred horse-power is transmitted, at a pressure of 2500 volts, from a mill three miles distant, where water power is available. The system is a three-phase one. The motors are the same in construction as the generators, and while being able to start themselves, run under load with perfect synchronism. The efficiency of the complete transmission from the power applied to the dynamo pulley to that delivered to the motor pulley is reported to be 80 per cent.

[1] *Elec. Review* (N.Y.), 1894, xxiv. 210; and see *ibid.*, 1895, xxvii. 82.

CHAPTER XXV.

ASYNCHRONOUS MOTORS.

MOTORS in which the rotation is produced by the induction of currents as the field shifts around, present the structural advantage that they can be made without commutator, and even without sliding contacts of any kind. The induction of these currents in an entirely detached structure depends upon the circumstance that the running is *asynchronous:* that is to say, that the revolutions made by the moving part do not correspond to the periodicity of the impressed currents.

Asynchronous motors may be grouped under two heads: (i.) *polyphase*; (ii.) *monophase.* In the former two or more alternate currents of equal period, but differing in phase, are employed to produce, as explained below, a *rotatory magnetic field;* this rotatory field tending to set up induced currents in all conducting masses placed within them, and by the reaction of these currents to rotate these masses mechanically. In the monophase class a simple oscillatory field is impressed by an alternate current, and this acting on a revolving system of conductors is, by the action of the induced currents, converted into a rotatory field with effective driving power.

As the subject has lately been treated *in extenso* in the author's work on 'Polyphase Electric Currents and Alternate-Current Motors,' the present chapter may be brief.

Production of a Rotatory Magnetic Field.—If an alternate current is led around a coil it produces along the axis of the coil an alternating or oscillating magnetic field. If there is an iron core the magnetic flux in it will be an alternating flux; that is to say, one that begins, increases to a maximum along a fixed direction, dies away, reverses along the direction and increases to a negative maximum, and dies away to begin the

cycle over again. The frequency of this alternating flux will be the same as that of the current. We have to show that by combining two or more alternating magnetic fields that are in different directions and in different phases we can produce the same effect as a magnetic field of constant intensity rotating in direction.

It is well known that a uniform circular motion can be decomposed into two rectilinear harmonic motions at right angles to one another, the two having equal amplitude, equal period and a phase difference of one-quarter period. Let P be a point uniformly revolving around centre O (Fig. 455); let the angle X O P = θ. The projections of the radius O P upon the two axes are O M and O N. If the radius O P be called r we have O N $= r \sin \theta$, and O M $= r \cos \theta = r \sin (\theta + 90°)$. While P revolves the point N will oscillate up and down the line Y Y′; the amplitude of its motion being equal to the radius of the circle. Also the point M will oscillate along the line X X′ with equal amplitude and in equal time; but O N will be at its maximum when O M has zero value, and *vice versâ*. It follows kinematically that a uniform circular motion may be produced out of two straight-line motions, by combining them at right angles, provided they are harmonic, of equal period, of equal amplitude and differing by an exact quarter period.

Mechanically this motion is equivalent to that of two pistons having equal travel, working by two connecting rods upon the same crank pin, but placed at right angles to one another (Fig. 456). If the cylinders are made to produce two rectilinear motions one ahead of the other by a quarter period in time, the apparatus will combine these motions into a true circular motion. If the two cylinders are set parallel side by side two cranks will be needed, one at right angles to the other.

A similar combination can be[1] magnetically effected. If an alternating current is led round a coil so as to produce an alternating or oscillating magnetic field along the line O X, and a second alternating current is led round a second coil so

[1] See Marcel Deprez, *Comptes Rendus*, ii. 1193, 1883.

as to produce a second alternating magnetic field along the line O Y, then the result will be a *rotatory* magnetic field, provided these two magnetic fields are of equal period and amplitude, and differ exactly a quarter in phase. If they are of equal period, but not of exactly equal amplitude, the result will be equivalent to an *elliptically*-rotating magnetic field; that is to say, one in which the strength and direction of the field is represented by the successive values of the radius vector drawn to an ellipse from its central point. An elliptically rotatory field will also be produced if the two component magnetic fields, though equal in period and amplitude, do not differ by exactly a quarter period. For a perfect rotatory

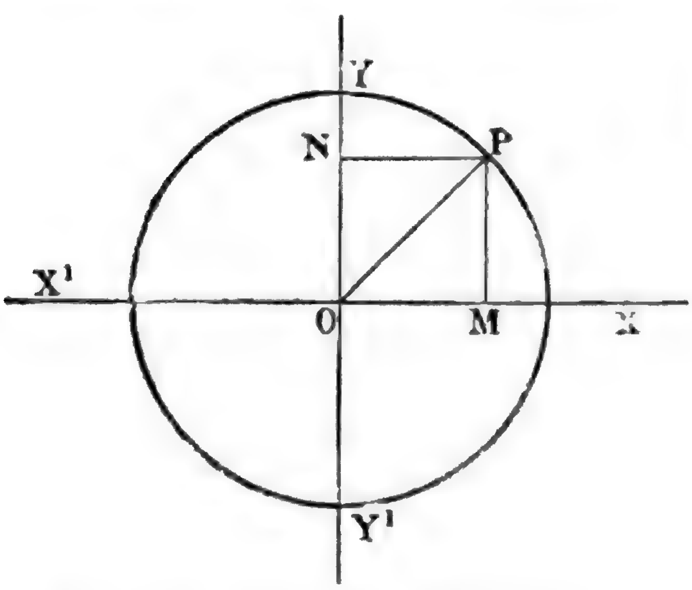


FIG. 455.—DEPREZ'S THEOREM.

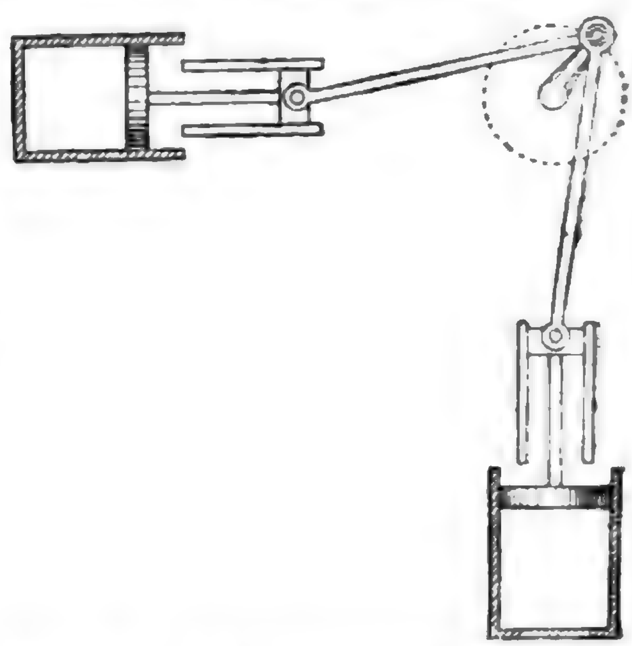


FIG. 456.—TWO-CYLINDER ENGINE.

field, corresponding to uniform circular motion, the two components must vary precisely as the sine and the cosine [1] of an angle respectively. The two-phase system of currents for producing a rotatory magnetic field is the electrical analogue of the two-crank mechanism.

This is not by any means the only combination that will produce a rotatory magnetic field. The mechanical analogues of the three-crank engine, and of the three-throw pump, at once suggest other solutions. In the former instance three cylinders are used, with three pistons which operate in successive phases differing by one-third of a period from one another.

[1] See also Ferraris, "Rotazioni elettrodynamiche," *Turin. Acad.*, March 1888.

If the three cylinders are set (as in a Brotherhood's engine) at 120° to each other (Fig. 457) their connecting-rods may actuate a single crank. If the three cylinders are set parallel side by side, then there must be three cranks spaced out in angular positions 120° from one another. If the angular positions of the cranks were not exactly 120° apart, the phase-differences of the motions will not be exactly one-third of the period. The time-phase of motion must be complementary to the space-phase of angle in the combining mechanism, otherwise the resulting motion will not be a *uniform* rotation. The famous three-phase system of currents (or *Drehstrom*) for producing a rotatory magnetic field, is the electrical analogue of the three-crank mechanism.

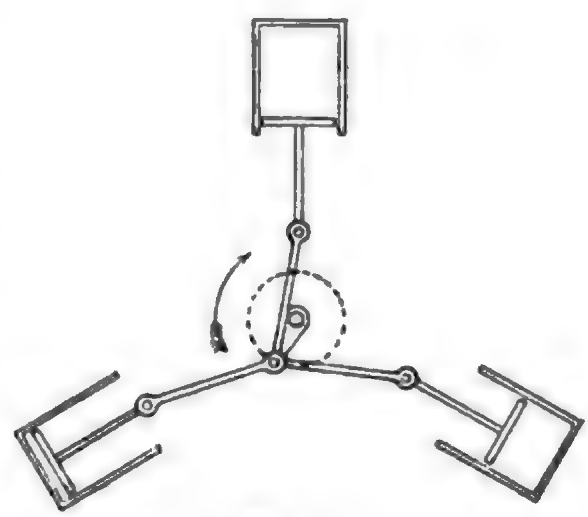


FIG. 457.
THREE-CYLINDER ENGINE.

We have then two main cases before us—the 2-phase method (sometimes called the "quadrature" method, or, less correctly, the "quarter-phase" method) and the 3-phase method (called by Dobrowolsky "Drehstrom"). The first 2-phase induction motor was described by Baily in 1879, who used commuted battery-currents. The idea of producing rotation by combining two or more alternate currents of different phase, seems to have occurred from the years 1885 to 1888 independently to several persons. Prof. G. Ferraris, Mr. C. S. Bradley, Mr. Nikola Tesla, Mr. Borel, and Mr. von Dolivo Dobrowolsky. Ferraris found that in such a rotating field not only will pivoted magnets rotate, but masses of iron, both solid and laminated, also disks and cylinders of copper, the drag on these being due to the eddy-currents generated in them precisely as in the classical experiments of Arago, in which copper disks were set in rotation in the presence of a rotating magnet. Fig. 458 illustrates a simple form of Ferraris's motor having a copper cylinder pivoted within two sets of coils A A and B B which lie at right angles to one another.

Ferraris discussed the elementary theory of the apparatus, pointing out that the inductive action would be proportional to the *slip*, that is to say, to the difference between the angular velocity of the magnetic field and that of the rotating cylinder, that the induced current in the rotating metal would also be proportional to this; and that the power of the motor is proportional jointly to the slip and to the velocity of the rotating part.

Consider a laminated iron ring, Fig. 459, wound with two pairs of coils A A′ and B B′, which are inserted in the circuits of a 2-phase generator. At the moment when the current in A A′ is a maximum, that in B B′ will be zero, the currents

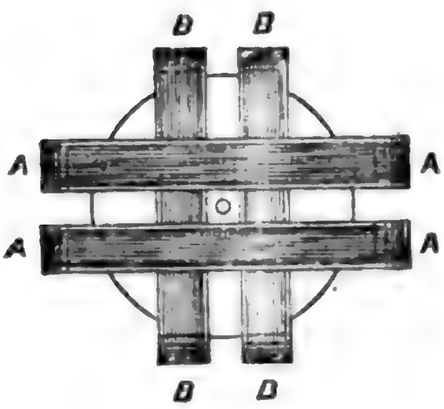


FIG. 458.—SIMPLE ROTATORY-FIELD MOTOR.

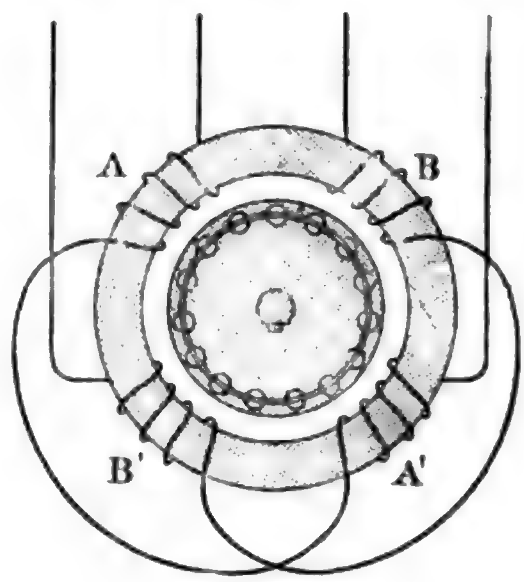


FIG. 459.

being in quadrature. The magnetizing effect of A A′ will tend to produce a magnetic field diagonally across the ring in the direction B B′. As the current in A A′ dies down, that in B B′ begins and increases, and therefore shifts the pole forward. When the currents in A A′ and B B′ have become equal, A and B will act together as one coil, while A′ and B will act together as another coil, the resulting poles lying now between B and A′ on the right and between B′ and A on the left. When the B current is at its maximum the poles will lie right under the middle of the A coils. Since there is an actual production here of a travelling polarity in the ring, it follows that any mere mass of iron, a cylinder for example, placed in the rotating field will be set into rotation, though

not synchronously; and a cylinder of copper would be dragged round by the eddy-currents induced in it. If the cylinder were to revolve at the same rate as the rotating magnetic field, there would be no eddy-currents and no driving force: the rotating part therefore tends to run up toward synchronism but never attains it; for without *slip* (i. e. difference of speed) there would be no induced currents. But if such eddy-currents were permitted to circulate at random in the mass of copper there would be much waste of power in heating, since the only useful currents for driving are those that flow at right angles to the magnetic lines and at right angles to the direction of motion, or, if oblique, their resolved parts in this direction. Hence it is better to make the moving part as an iron core surrounded by appropriate closed coils within which the induced currents are confined. A special form excellent for small motors consists of a cylinder of laminated iron within the periphery of which are embedded a number of stout insulated copper conductors lying parallel to the axis, their ends being united together so that they form closed circuits. A ring of copper at each end—forming with the conductors a sort of squirrel-cage of copper filled with iron—serves to short-circuit the conductors. A short-circuited structure of this kind is shown in Fig. 460.

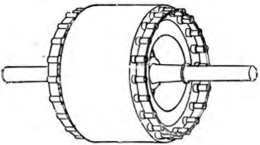


FIG. 460.—ROTATING PART OF BROWN'S MOTOR.

When such rotating combinations of copper and iron are used it becomes a question which part of the machine should

be considered as armature, and which as field-magnet. If the ring is regarded as armature, then the copper and iron combination must be looked upon as a field-magnet which is self-magnetized by the eddy-currents in the copper, and which is continually trying to catch up the rotating poles outside it so as to reduce those eddy-currents to a minimum and keep its magnetic polarity constant. If, however, the ring be looked upon as the equivalent of a rotating magnet, then the combination of copper and iron may be considered as an armature in which currents are induced, and which is driven by the

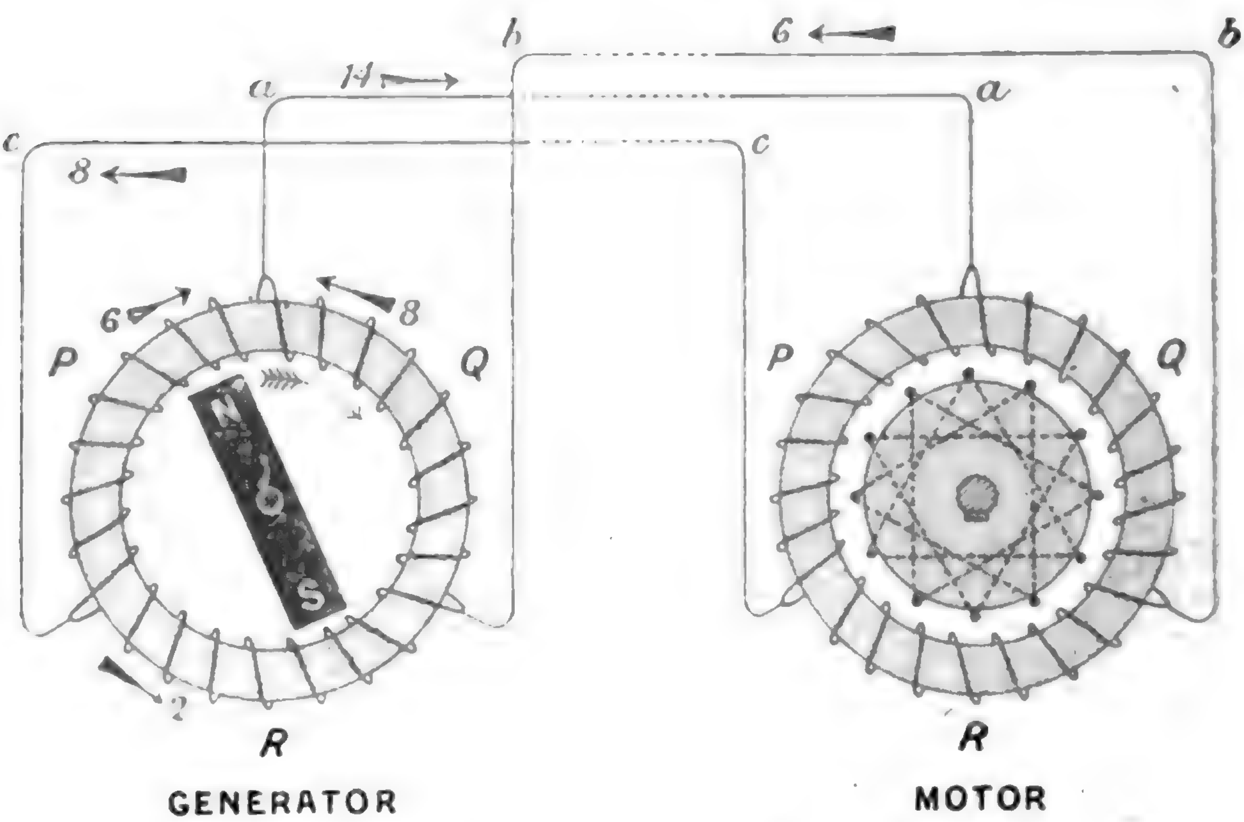


FIG. 461.—ILLUSTRATION OF 3-PHASE TRANSMISSION.

reaction of these currents. The former is certainly the more correct view: but to avoid ambiguity it is better to call the revolving mass by the term *rotor*; while the stationary part which receives the primary currents may be called the *stator*.

The case of 3-phase currents is illustrated by Fig. 461, where the generator is represented by a magnet revolving within a ring-armature, generating three currents differing 120° in phase from one another. The rings are wound with three coils joined up at their ends and united to three lines. The current in any one line at any instant is equal to the

algebraic sum of the currents in the other two; and, with the arrangement shown, the phase of the currents in any one of the lines is intermediate between the phases of the currents in the two coils feeding it. Further, in the motor the current in P differs in phase from the currents in *c* and *a*, being $\frac{1}{12}$ period in advance of the leading current. As the magnet rotates in the generator a pair of travelling poles will, as before, be produced in the ring of the motor. It will be noted that the coils here constitute a closed circuit. There are indeed several ways of connecting up three coils so as to produce the rotatory effect, the following being possible: (1) each of the three coils might be independently joined by two wires to the ends of the three corresponding coils, requiring six lines; (2) three ends of the three coils might be independently

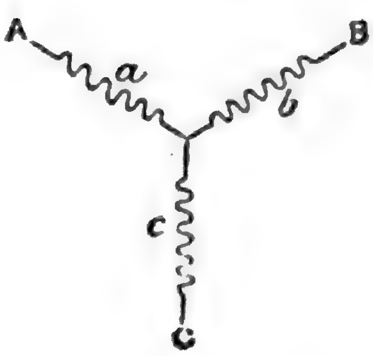


FIG. 462.
STAR COMBINATION.

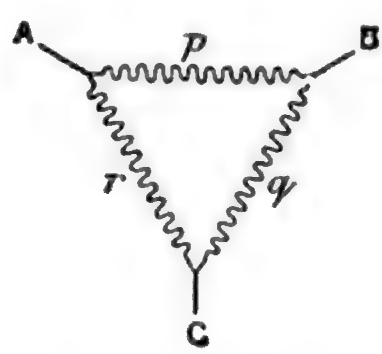


FIG. 463.
MESH COMBINATION.

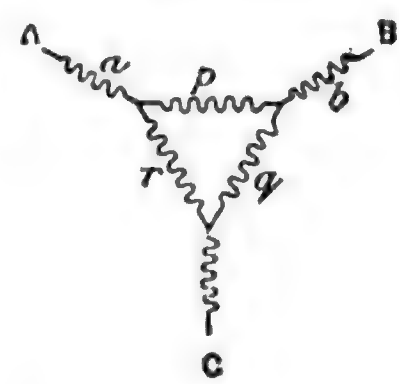


FIG. 464.—STAR AND MESH COMBINATION.

joined by three wires to the three corresponding ends of the coils in the motor, their three other ends being united to a common return line, so involving four wires; (3) the three coils *a*, *b* and *c* may be simply joined at a common junction (Fig. 462), from which they branch star-wise each to its own line; (4) the three coils may be joined as *p*, *q* and *r* in Fig. 463, in a closed mesh joined with the three lines at its corners. In this case the phases of the currents in *p*, *q* and *r* are intermediate between those of the three currents in the lines; (5) six coils may be used as in Fig. 464, which shows the way of getting a 6-phase effect out of a 3-phase current by combining the star and mesh arrangements; (6) by merely winding a coil left-handedly instead of right-handedly the phase of its magnetizing force is reversed. For example, a reversed coil inserted

in *a* (in Fig. 461) would give an effect differing 180° in phase from *a*, and therefore intermediate between *b* and *c*.

The mode in which the three currents overlap in phase is shown in Fig. 465, the phase-difference being here 120°. Three currents with phase-difference 60° will also serve for rotatory work, and can be converted into three of 120° by merely inverting the connexions at the ends of one of the three coils.

Star and mesh combinations may also be applied to 2-phase systems. The two circuits of the Niagara generators are kept separate, four lines being required; but in many cases three lines would suffice, one of them serving as a common return for the two circuits.

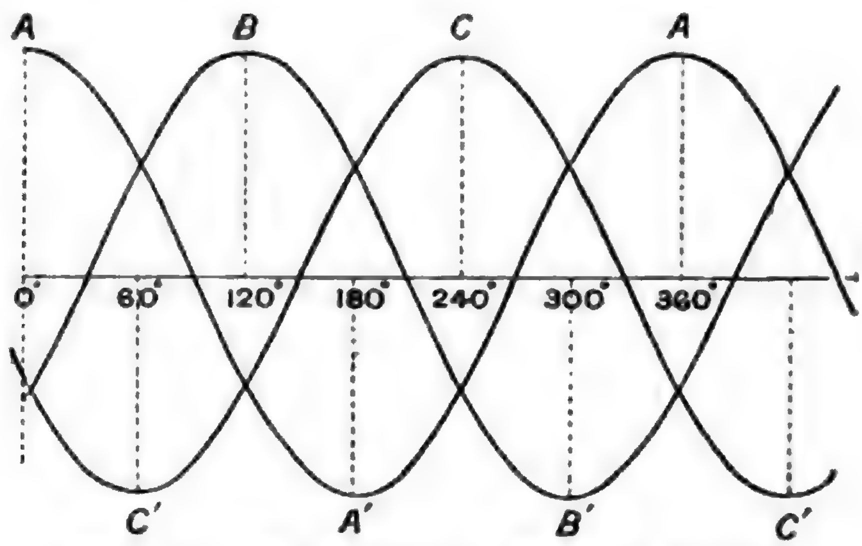


FIG. 465.—THREE-PHASE CURRENT CURVES.

When mesh combinations are used the current in the limb of the mesh as measured by amperemeter differs in value from the current in the line. For a 2-phased system the current in the limb is $\frac{1}{\sqrt{2}}$ of the current in the line. For a 3-phase system the limb-current is $\frac{1}{\sqrt{3}}$ of the line-current. When star combinations are employed, the limb-currents are the same as the line-currents, but the voltages between line and line differ from the voltages between any one line and the common junction. For a 2-phase system with 4-ray star connexion, the voltage between two adjacent lines is $\sqrt{2}$ times as great as that from line to centre; while with a 3-phase system it is $\sqrt{3}$ times as great.

Bradley in 1887 described a 2-phase motor (Fig. 466) with mesh connexions; the current being brought in by four slip-rings. This, however, was a synchronous motor having a fixed external magnet. In 1889 he described a 3-phase machine, having a similar armature connected at three symmetrical points to three slip-rings.

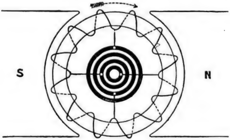


FIG. 466.—BRADLEY'S 2-PHASE MOTOR.

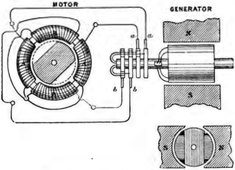


FIG. 467.—TESLA'S 2-PHASE SYSTEM.

Tesla in 1887–88 designed many combinations of which the fundamental notion was the progressive shifting of the field. In Fig. 467 a generator is shown wound with two coils, the free ends of which are connected to insulated contact-rings

on the shaft. From four brushes that press on the rings four wires are led away to the motor. This is, in fact, a simple 2-phase generator, inducing two independent currents in quadrature. The motor is shown as a ring having wound upon it four coils, two of which are connected in circuit with one pair of wires, the other two being in the other circuit. They tend to co-operate in pairs to produce magnetic poles on diametrically opposite parts of the ring. Within the ring is pivoted as rotor a disk D of iron, preferably cut away at its sides so as to form an elongated body; and turning so as to convey from side to side of the ring the greatest number of magnetic lines. It was found that this form was not essential to rotation, since a circular disk of iron was also set revolving. In a series of eight diagrammatic figures Tesla explained the successive phases through which the coils of the generator pass during one revolution, and the corresponding and resulting changes of magnetism produced in the ring of the motor.

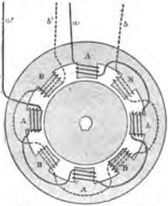


FIG. 468.—MULTIPOLAR DESIGN.

By adopting a multipolar design the speed can be reduced though the frequency of alternation remains the same. Fig. 468 shows a design by Tesla for using a tetrapolar magnetic field having four poles in the A circuit (alternately N and S poles), and four intermediate poles in the B circuit. In such a case the progression of the field is not a uniform rotation. The field of a pole at A does not shift round to the next pole at B. What happens is that the magnetism of the A pole dies out, while fresh magnetism grows in the neighbouring B pole.

The famous 3-phase transmission of power from Lauffen to Frankfort in the autumn of 1891 did much to bring into

notice the advantages of polyphase methods for electric power purposes. Through three copper wires, each 4 millimetres in diameter, and 110 miles long, 100 H.P. was transmitted with an efficiency of 75 per cent., the pressure being raised by transformers to about 8000 volts (see p. 697.) Particulars are given in the author's work on Polyphase Electric Currents.

Modern Polyphase Motors.—In modern motors both stator and rotor are built up of stampings of soft iron pierced with holes or slotted to receive the conductors. Fig. 469 gives about ¼ size the stampings for a 4-pole, 6-H.P., 2-phase motor designed by Brown; the rotor being of the short-circuited squirrel-cage pattern (Fig. 460) with 37 conductors. This motor is intended for 100 volts at a frequency of 40 periods, and runs at 1200 revolutions per minute. Plate XVIII. gives scale drawings of a 3-phase motor of 100 H.P., taking current directly from high-pressure mains at 5000 volts, with a frequency of 40 periods per second and a speed of 600 revolutions per minute. The rotor, which is about 30 inches in diameter, has 96 holes through which insulated copper conductors are threaded, and joined up in a wave-winding constituting a 3-branched star, of which the three outer ends are led down through the shaft to three slip-rings to permit of an external starting-resistance being applied. The torque at starting is greater when such resistances are inserted in the secondary circuit (see p. 681). Fig. 470 gives an external view of a 2-phase 120 H.P. motor built upon the same carcase, but with different windings, to work at 2000 volts. In this case the starting resistance is attached inside the rotor, with a simple mechanism passing out through the end of the shaft to short-circuit it when the motor has started. In this way the need of slip-rings is avoided, the rotor having no external connexions of any kind.

These rotatory-field motors were brought to a high pitch of perfection by the Oerlikon Co., and by Brown, Boveri & Co.: and more recently the Westinghouse Co. has brought out many fine designs. On the Continent of Europe several large central stations and many factories are now equipped

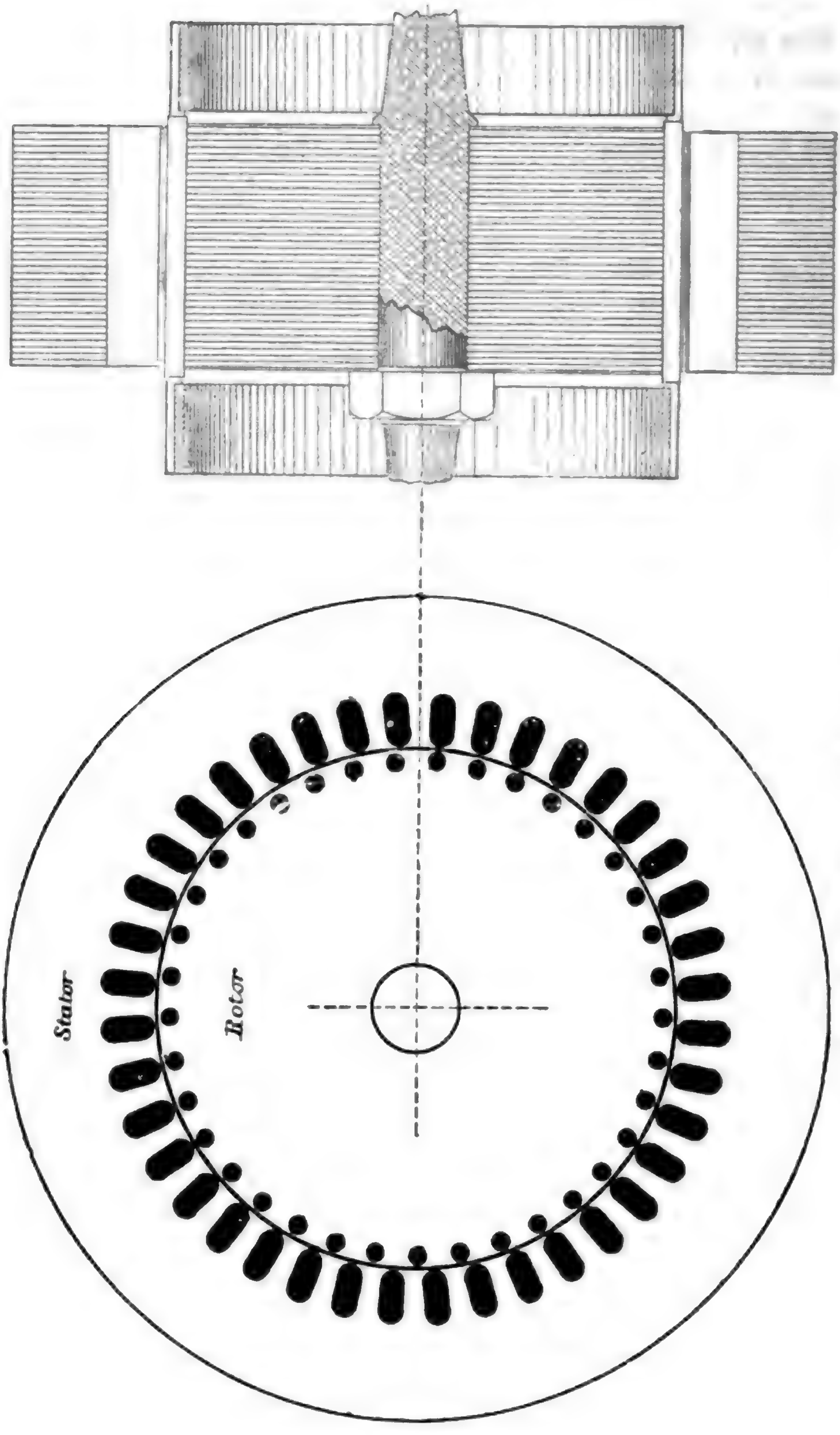


Fig. 469.—Stator and Rotor Stampings (Brown).

with polyphase systems. The efficiency of the polyphase motors is very high, certainly not inferior to that of continuous-current motors of equal power and cost.

ELEMENTARY THEORY OF POLYPHASE MOTORS.

For the sake of simplicity we will take a bipolar machine, the iron of which is of the general shape shown in Fig. 469. Suppose that a rotatory magnetic field is produced by either 2-phase or 3-phase currents in the stator.

FIG. 470.—TWO-PHASE MOTOR OF 120 HORSE-POWER (BROWN).

The currents in the rotor also produce a magnetic field which, compounded with that of the stator, gives rise to a resultant rotating field. It is to this resultant field that the electromotive-forces in the conductors, and the torque, are due. We will take it as a uniform flux flowing diametrically through the rotor and cutting the conductors of both stator and rotor as it revolves.

Let Ω stand for angular speed of the rotatory magnetic field $= 2\pi n$ in a bipolar machine, where n is the frequency of period. If the machine is multipolar having m pairs of poles then $\Omega = 2\pi n \div m$.

Let ω stand for angular speed of the rotating part, or *rotor* of the machine, $= 2\pi n_2$, where n_2 is the actual number of turns per second.

Let T stand for the torque between the stator and the rotor.

Let W stand for the power (total watts) communicated by the stator to the rotor.

Let w stand for the power (useful watts) actually used in turning the rotor.

$\Omega - \omega$ is the *slip* of the rotor with respect to the field, or is the difference of their angular speeds. If the field has an angular speed $\Omega - \omega$ greater than that of the rotor, it is clear that the inductive action on the circuits of the rotor will be exactly the same as if the rotor were revolved backwards with a speed $\Omega - \omega$ while the field stood still.

$W - w$ is the power wasted in heating the conductors and iron of the rotor, since it is the difference between the total power supplied to the rotor and the power it utilises.

Now W is proportional to T and to Ω, and therefore, by choosing suitable units may be written $W = T\,\Omega$.

And w is proportional to T and ω, and may be written $w = T\,\omega$.

Hence, dividing the last equation by the preceding,

$$\frac{w}{W} = \frac{\omega}{\Omega}.$$

From this we see that the efficiency of the *rotor* is the same as the ratio of the two speeds. The efficiency of the stator will be considered presently.

Further, the rotatory-field motor is simply a sort of running transformer, of which the stator and rotor windings constitute respectively the primary and secondary. Now, if ω were made $= \Omega$ there would be no induced currents in the rotor conductors, the stator would then simply act as a choking coil; hence, it follows that if the condition of supply of the primary currents is that of constant voltage, the magnetic flux through the machine, rotating with speed Ω, will have an approximately constant value at all loads, just as the flux in the core of an ordinary transformer has. This, of course, is only true when

the current in the stator coils is unrestricted; it is not true, for instance, if a resistance is put in series with the stator coils, or when the motor is starting without any resistance in its rotor circuit, as will be seen hereafter. Further, if there is very little magnetic leakage in the gap between stator and rotor (as is indeed the case in well-designed motors), the only electromotive-forces in the rotor conductors will be those produced by the resultant magnetic field, and therefore the maximum currents in them will occur when the conductors are in that part of the field where the flux density is a maximum. And as the flux is constant at all loads (subject to the above conditions), it follows that the torque will be proportional to the currents in the rotor. But these are proportional to the slip $\Omega - \omega$: hence, also, it follows that T will be proportional to $\Omega - \omega$, and may be written $T = b\ (\Omega - \omega)$, where b is a constant depending on the strength of the field, the radius of the rotor, and the length and resistance of the conductors of the rotor.

We may now write;—

$$\text{Useful watts } w = b \,.\, \omega\,(\Omega - \omega).$$
$$\text{Total watts } W = b \,.\, \Omega\,(\Omega - \omega).$$
$$\text{Wasted watts } W - w = b \,.\, (\Omega - \omega)^2$$

Hence we may at once apply the now well-known diagram of motor efficiencies, by drawing (Fig. 471) a square A B C D, having its side A B numerically equal to Ω, and cutting off a piece B F equal to ω. The area A F H D represents the total watts supplied, the area AFGK, or G L C H, the watts utilised, and the square K G H D the watts wasted in heating the conductors of the rotor. The efficiency will approach unity as F moves up towards A; and, as with continuous-current motors, if it were not for the

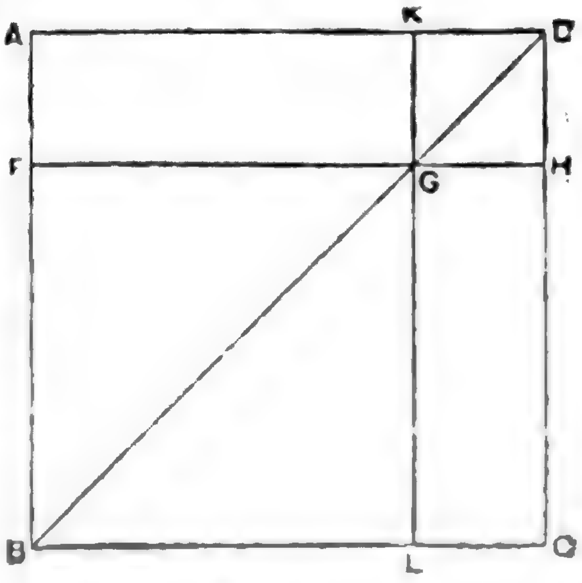


FIG. 471.

weakening of the field by armature reaction, the output would be a maximum when $\omega = \frac{1}{2}\Omega$, the efficiency being then only 50 per cent. We shall see presently that when the motor is running at much below its proper speed, magnetic leakage and other causes play such an important part that the torque is actually less than at a higher speed. Fig. 471 is, however, applicable to cases of normal running, and shows how these rotatory-field motors behave in an exactly similar manner to continuous-current motors.

In good modern rotatory-field motors the slip is only, at the most, about 4 per cent., except for very small sizes of machine, where it may be 10 per cent. at full load.

In the above investigation no account has been taken of the loss due to heating in the conductors of the primary or stator circuit. This, like the ordinary C^2R loss in the exciting circuit of any dynamo, is but a small percentage of the whole energy supplied. Neither has any account been taken of hysteresis losses in the iron of the stator, which also have to be supplied, as it were, by additional excitation, but are small in a well-designed machine. Losses by hysteresis or by eddy-currents in the iron of the rotor will, like the friction of the journals, deduct from the available power, but these are necessarily very small since the reversals of the magnetism in the rotor are proportional not to Ω but to $\Omega - \omega$.

Resultant Magnetic Flux in Motor.—It was pointed out above, from consideration of transformer analogies, that the magnetic flux in the motor is of approximately constant value at all normal loads. We may take it that in the air gap between rotor and stator the flux-density varies approximately as a sine function around the periphery from point to point. Let the density of this flux in the direction in which it is a maximum be called **B**. This flux-density, like the flux-density in a transformer core, is the result of the magnetizing actions of both the primary and the secondary windings. Kapp has given[1] a discussion of the reaction which may be summarized as follows.—

Take a line **B**, to represent (Fig. 472) the maximum of

[1] Gisbert Kapp, *Electric Transmission of Energy*, 1894, p. 310.

the flux-density in the motor; in a bipolar machine it may be considered as revolving clockwise around O as a centre, with an angular speed Ω. This field is due to the joint action of the impressed field excited by the primary currents in the stator, and of the induced field excited by the secondary currents in the rotor. These rotor currents are in phase with the resultant field (if there is no magnetic leakage), and proportional to it, and to the slip. They may be represented by a length c, set off along the side **B**. This current c tends to produce a cross-magnetization, p. 73, proportional to itself. Let the line b at right angles to **B** represent this cross field. Here $b = k\,c$ where k is a coefficient depending on the reluctance of the magnetic circuit and the number of windings on the rotor. Complete the triangle **B** $b\,a$ by drawing the line a. Then a represents in magnitude and phase the magnetic field that must be impressed by the primary currents in the stator, since **B** is the resultant of a and b. The angle β is the angle by which the current in the rotor lags behind the impressed field.

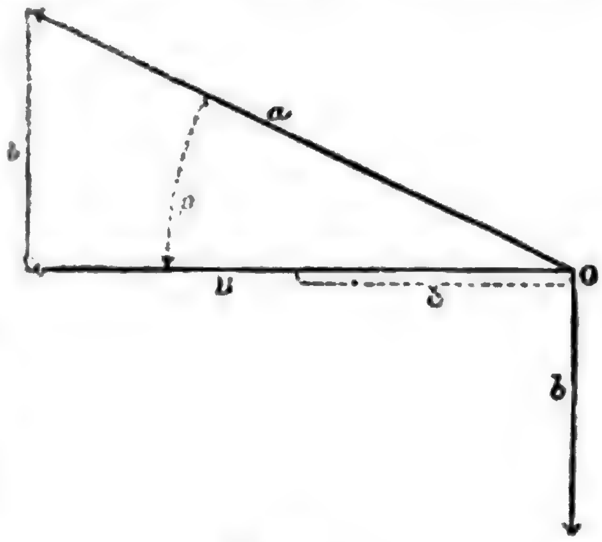


FIG. 472.

Further, since the torque is proportional to both **B** and c—that is to **B** and b—the area of the triangle a **B** b will represent the torque.

Moreover, since c is proportional to the slip,[1] and to **B**, and to a constant depending inversely on the resistance R in the rotor circuit, we may write

$$c = \frac{\mathbf{B} \times \text{slip}}{\mathrm{R}};$$

$$\text{or slip} = \frac{c\,\mathrm{R}}{\mathbf{B}};$$

[1] "Slip" is here used to denote an angular speed, namely $(\Omega - \omega)$. Some writers use it to denote the ratio between the two speeds, that is to say $\frac{\omega}{\Omega}$.

and substituting $b \div k$ for c,

$$\text{slip} = \frac{b}{\mathbf{B}} \times \frac{\mathrm{R}}{k}:$$

but $b \div \mathbf{B}$ is $\tan \beta$, hence slip is proportional to $\mathrm{R} \tan \beta$. That is to say, if the slip is great the angle of lag β will be great.

Conditions of Operation.—There are three chief stages of operation to be considered; and for the present we will consider the supply voltage constant.

(i.) *Starting.*—Here $\omega = 0$, and slip $= \Omega$. Rotor currents enormous, primary currents also enormous. Therefore, β the angle of phase-difference between primary currents and resultant field very large. Torque would be enormous if there were no magnetic leakage (see p. 681).

(ii.) *Running at Light Load.*—Here ω is very nearly equal to Ω; and as slip is small, rotor currents will be small, and their reaction small. Angle β will be small, and a will not be much larger than $\mathbf{B}$.

(iii.) *Running with Heavy Loads.*—Here $\Omega - \omega$, the slip, must be enough to allow of the generation in the rotor of currents enough to produce the necessary torque at the actual speed of rotation.

In addition to the above, if the speed is artificially brought up to synchronism by supplying from without power to overcome friction, &c., there will be no rotor currents and no torque. If the speed is artificially increased beyond this, so that the rotor runs faster than its field, power will be consumed in driving it, and it will act as a generator, pumping back current into the supply network, as we shall see presently (see p. 685; also p. 606).

Starting Torque.—In the above we have considered a motor working under normal conditions, so that the rotor currents are not excessive and the effect of magnetic leakage has been neglected. When, however, the motor is being started, the slip is so great that enormous currents would be generated in the rotor circuit if of low resistance. These currents would call for very large currents in the primary coils to keep up the magnetic flux, just as in a transformer.

The effect would be threefold. In the first place, a considerable fraction of the pressure of supply would be lost upon C^2r losses in the stator coils. Secondly, the ampere-turns of the stator and rotor coils, opposing each other with very great magnetomotive-forces, would force a number of lines along paths which do not thread through both sets of coils (for example, leakage would appear along the air-gap), and these lines would be the cause of electromotive-forces in the stator and rotor coils, in addition to the electromotive-force produced by the common resultant field, and have a choking effect upon the currents in these coils. Thirdly, not only is the true resultant field B diminished by the above causes, but the little that remains is out of phase with the current in the rotor circuit, so that the torque is very much reduced instead of being increased by excessive slip when the rotor circuit is of low resistance. This is very simply exhibited in Mr. Kapp's construction. When the slip is great, the triangle $a\,\mathsf{B}\,b$ will become of the form of Fig. 473; for if slip is proportional to R tan β, and R is small, tan β must be very great, β will be near 90°, the impressed field a is limited by the foregoing considerations, so the torque (represented by the area) will be very small. If we increase R we necessarily decrease tan β, making B greater and the area greater, and so we get a greater starting torque. Thus, introducing a non-inductive resistance into the rotor circuit at starting enables the machine to start with a greater torque.

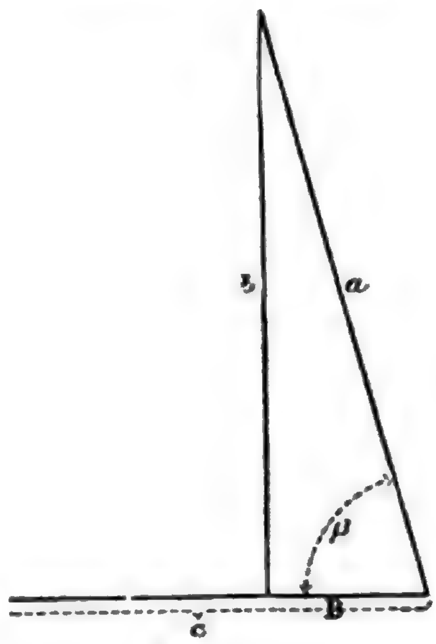


FIG. 473.

Relation between Torque and Slip.—In order to get an equation for the torque in terms of the slip and the resistance of the rotor, we note that from Fig. 472 it follows that

$$b = a \sin \beta,$$

and

$$\mathsf{B} = a \cos \beta.$$

Now, from the equation—slip $= \frac{b}{\mathbf{B}} \times \frac{R}{k}$, we get $\frac{\text{slip}}{R} \times k = \frac{b}{\mathbf{B}}$.
Therefore, by merely altering the scale of Fig. 472, we can rename the sides of the triangle as shown in Fig. 474, where s stands for the slip.

From this we see that $\sin \beta = \frac{k\,s}{\sqrt{R^2 + k^2 s^2}}$, and $\cos \beta = \frac{R}{\sqrt{R^2 + k^2 s^2}}$.

Therefore the torque T, which is proportioned to $b \times \mathbf{B}$, is

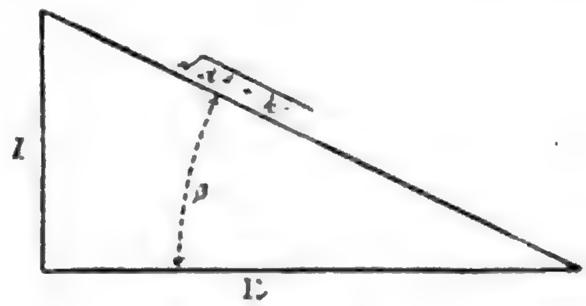


FIG. 474.

proportional to $a^2 \sin \beta \cos \beta$; and therefore, writing q as a quantity involving a^2 and constants depending on construction, we have

$$T = q \cdot \frac{s\,R}{R^2 + k^2 s^2}.$$

Here we are assuming that a, the impressed field, is constant (see p 681).

If we wish to see graphically what this equation means, we may then plot out the relation between T and s as a curve, assuming a definite value for R.

Take the line O X (Fig. 475) to represent the speed of rotation of the magnetic field, and cut off from it a part O Q to represent the speed of the motor. Then the remainder Q X represents the slip. This is equivalent to plotting the slip backwards from X. The vertical ordinates then represent the values of the torque as calculated from the equation. For example, when Q X is taken as s; P Q is plotted to represent the corresponding value of T. Thus, beginning at X where the slip is zero, we get a curve X P t_1, which rises

steeply, comes to a maximum, and dies away to the value O t, which is the torque at starting. The torque has a certain maximum value for which $\beta = 45^\circ$. It will be noted that the steep end part of the curve is nearly straight, being an asymptote to a straight line, which would represent the relation between torque and slip if the current in the stator were unrestricted and the magnetic field constant. In fact, this line corresponds to the expression $T = b\,(\Omega - \omega)$ on p. 677. Or if in our present equation we consider that values of s are small compared with R, the equation might be written $T = q\,\frac{s}{R}$, giving a straight line law. At the other

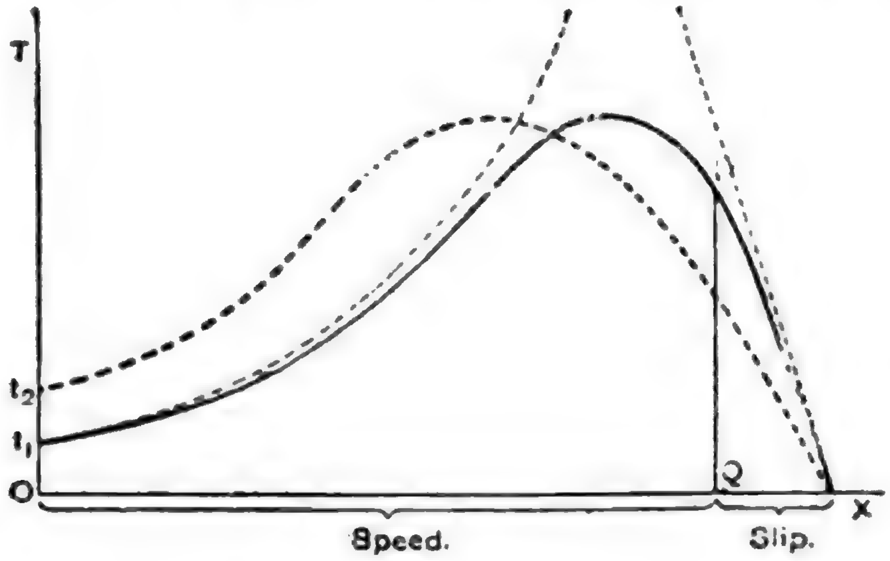


FIG. 475.

end of the curve, where slip is great, the curve is hollow. Here we may approximate by supposing that s is very great compared with R, or that R^2 is small compared with s^2; in which case the equation reduces to $T = q\,\frac{R}{s}$. This is the equation to a hyperbola (also shown in dot). When the motor is at rest $s = \Omega$, or O Ω = zero, giving at O t_1 the value $T = q\,\frac{R}{\Omega}$. That is to say, *at starting*, the torque is proportional to the resistance of the rotor. If we then assign a higher value to R, and plot out a new set of ordinates, we obtain a new curve (shown in dotted line) which also starts at X, rises to a maximum of the same height as before, and then falls, but this time to t_2. The effect, then, of

introducing more resistance is to raise the torque at starting; but it also has the effect of causing the maximum torque to occur when the slip is greater. The motor gives out practically the same power as before, but runs with a greater difference of speed between its speed at light load and its speed at full load. And the efficiency at full load is diminished. If, with a 5 per cent. slip and a 95 per cent. efficiency, we do not get a sufficient starting torque, we can get it by introducing resistance, and contenting ourselves (at full load) with, say, a 10 per cent. slip, and a 90 per cent. efficiency. And one understands the reason for the modern device of constructing the rotor so that a resistance can be put in at starting, and then short-circuited as soon as the rotor has got up a fair speed.

In the various theories of the rotatory-field motor[1] the subject is attacked from many different points of view, but, through whatever mathematical intricacies it has passed, the expression for the torque is of the general form

$$T = q \frac{s\,R}{R^2 + k^2 s^2}.$$

The above method of deducing the formula, though incomplete in so far as it does not contain symbols for all the quantities concerned, perhaps has the advantage of keeping clearly in view the main principle, and enabling the student to follow the physical meaning of the expressions throughout. The quantity k, it will be remembered, is a constant, depending upon the reluctance of the magnetic circuit and the number of windings on the rotor. It is, in fact, the self-induction of one complete turn of conductor on the rotor. The quantity q involves a^2 and total number complete turns upon the rotor. In comparing with the formulæ given by other writers, it must be remembered that s is an angular speed, and is equal to $2\pi(n - n_2)$ (see p. 676).

[1] By Duncan, Hutin and Leblanc, Sahulka, Picou, Arnold, Ferraris, Reber, Steinmetz, De Bast and others. See the author's work on *Polyphase Electric Currents.*

Steinmetz gives the formula for finding the torque in pounds at 1 foot radius in the form

$$T = \frac{f e^2 g^2 s R}{R^2 + k^2 s^2},$$

to use our own symbols ; g being the ratio of the secondary turns to the primary turns, and

$$f = \frac{550}{746 \pi p n},$$

where n is the frequency, and p the number of poles. Steinmetz's theory is very complete in this respect, that he takes

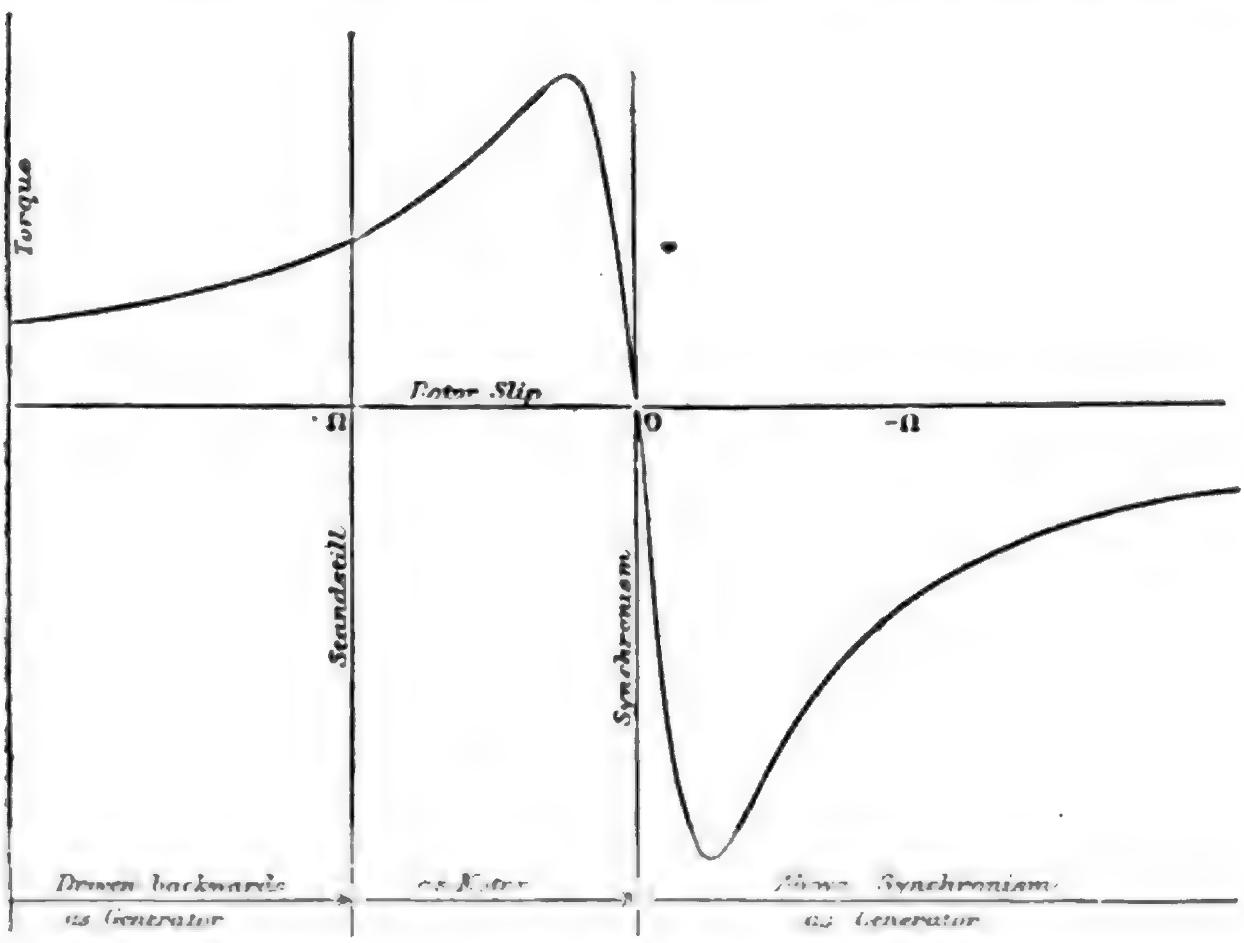


FIG. 476.

into account both leakage and hysteresis, and gives an expression for e, the counter electromotive-force in the stator conductors, in terms of the impressed volts, and an expression involving these quantities. Plotting values for torque at different amounts of slip he gives the curve shown in Fig. 476, which is of the same character as that given in Fig. 475, only

extended in both directions. If the speed of the motor is run up by mechanical means beyond synchronism, the torque becomes negative and the machine acts as a generator, giving the lower branch of the curve. If, on the contrary, the motor is turned in the sense opposite to the rotation of the field, the torque decreases as shown on the left of the figure.

The Stanley-Kelly Two-phase Motor.—This motor has the characteristic peculiarity that though a two-phase motor, the two magnetic fields are kept independent and are not combined to form a rotatory field. The stator (Fig. 477) consists of two parts, each of which is multipolar, and which are "staggered" with respect to one another. Each simply produces an alternating field. The revolving part consists of two rotors side by side (Fig. 478), the windings of which are interconnected, so that the wire which lies directly under the poles in one of the stationary armatures, is in series with the

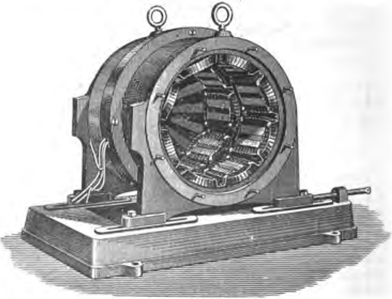


FIG. 477.—STATOR OF STANLEY-KELLY MOTOR.

wire that lies between the poles in the other. So connected each rotor acts alternately as a motor, to receive current and

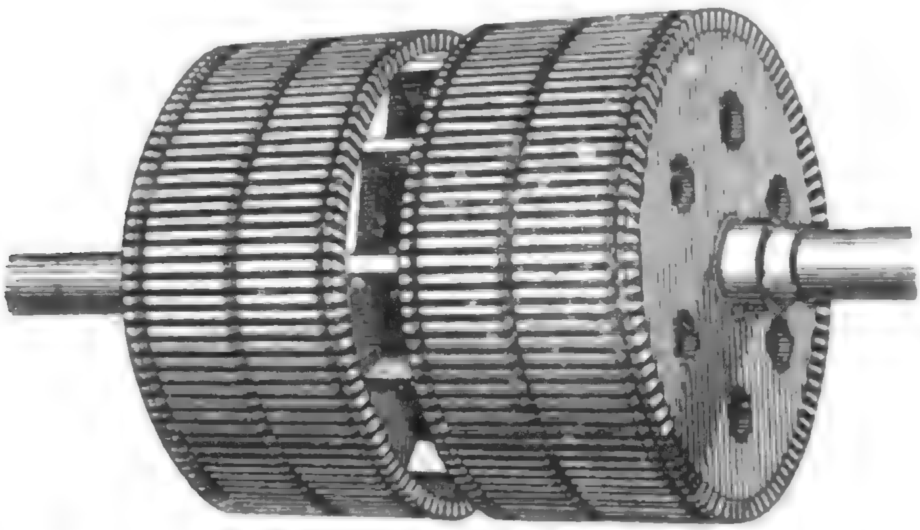


FIG. 478.—ROTORS OF STANLEY-KELLY MOTOR.

be driven by it, and as a transformer to send current to the other rotor. The windings on the two rotors together are closed, having no external connexions or commutator.

MONOPHASE MOTORS.

As soon as polyphase asynchronous motors had reached the stage of practical success, it became evident that monophase asynchronous motors might be constructed on analogous lines. Many years ago De Fonvielle discovered that an iron disk pivoted within a coil supplied with an alternate current was maintained in rotation if once started in either direction. Even before the introduction of polyphase methods the fundamental fact had been discovered by Prof. Elihu Thomson, that if a short-circuited armature is set into rotation between the poles of an alternating electromagnet, it will tend to go on in the direction of its motion and increase its speed. The alternating magnetic flux through a non-moving rotor will induce strong currents in those conductors which enclose it; but there will be no more tendency to turn in one direction than in the other. But Elihu Thomson found that owing to the lag caused by self-induction, the current in the closed circuit reacts, tending to produce a secondary magnetic field which is out of phase with the primary or impressed field.

Hence, if this secondary field is compounded at an angle with the primary field, the resultant action will be equivalent to a rotatory field.

In the course of his observations on the effects of alternate currents,[1] in 1886–7, Elihu Thomson observed that a copper ring placed in an alternating magnetic field tends either to move out of the field or to turn so as to set itself edgeways to the magnetic lines. He took an ordinary continuous-current armature placed in an alternating field, and having short-circuited the brushes, placed them in an oblique position with respect to the direction of the field. The effect was to cause the armature to rotate with a considerable torque. The conductors of the armature acted just as an obliquely placed ring, but with this difference, that the obliquity was continuously preserved by the brushes and commutator, notwithstanding that the armature turned, and thus the rotation was continuous.

A closed squirrel-cage rotor, like Fig. 460, when once started in an alternating (bipolar) field, tends to run up into synchronism; that is to say, if there were no friction it would make exactly half a turn during each reversal of the primary current. But if there is any work done in turning, then it will run slower, the *slip* being proportional (as in the polyphase motors) to the torque. The only trouble then is to start the motion.

Monophase motors may therefore be built on lines precisely similar to the polyphase motors already described. The rotor, for small sizes, may be a simple squirrel cage; for larger sizes it will be a wound structure, with arrangement for inserting a starting resistance. The stator will be wound with appropriate windings to receive the primary current, and with an auxiliary winding to be used at starting, as described below, and then either to be cut out or else thrown into the main circuit.

[1] Elihu Thomson, "Novel Phenomena of Alternating Currents," *Elec. World*, (N.Y.), May 28, 1887. See also J. A. Fleming, "On Electro-magnetic Repulsion," *Proc. Royal Institution*, March 1891; and *Journ. Soc. of Arts*, May 14, 1890.

Splitting the Phase.—The way in which monophase motors are commonly started is to superimpose upon the alternating field an oblique field differing in phase. This is usually done by having additional coils on the stator fed by a current that is out of step with the current in the main coils, and it is necessary to have some device which will cause a difference in the phase of the currents in the two branches. This operation of *splitting the phase* may be performed in many ways. Ferraris produced rotation in his motor by connecting one of the pairs of coils in the circuit of an ordinary alternate current, whilst the other pair were connected as a shunt to the circuit, with an inductive resistance included in order to retard the phase. Borel attained a similar result by using iron cores in one pair of coils.

We have seen (p. 563) that in circuits possessing resistance and self-induction the tangent of the angle of lag of the current behind the electromotive-force is equal to $p\,L/R$. If, therefore, we have a comparatively large self-induction in one branch of the circuit, and comparatively large resistance on the other, the phases of the currents will differ by nearly 90°. This difference in the self induction of the branches may be caused either by the difference in the number of turns of wire in the coils on the stator and the arrangement of the iron around them, or it may be caused by putting in series with one of the branches a coil of wire on an iron core. A non-inductive resistance may be introduced into the other branch.

A difference in phase can also be produced by giving one of the branches capacity by means of a condenser, capacity having the effect of giving the current a lead. The kind of condenser usually employed for this purpose is an electrolytic condenser, consisting of a number of iron plates with a solution of carbonate of soda between them.

Split-phase Motors.—This device of procuring a difference of phase at starting may also be made use of for the permanent running of a motor. Two-phase motors were designed by Tesla in which the two sets of poles were wound with coils having different resistances and inductances. They

only need to be supplied, however, from a single source of alternating current.

Theory of Monophase Motors.—Prof. Ferraris[1] has given a simple method of treating this subject in which the alternating magnetic field is regarded as being resolved into two magnetic fields rotating in opposite directions. It is a familiar point in mechanism that any simple harmonic rectilinear motion may be resolved into two equal circular motions in opposite directions. Fig. 479 illustrates one way of doing this, the mechanism being well known to engineers. The amplitude of the original motion is equal to the diameter of each

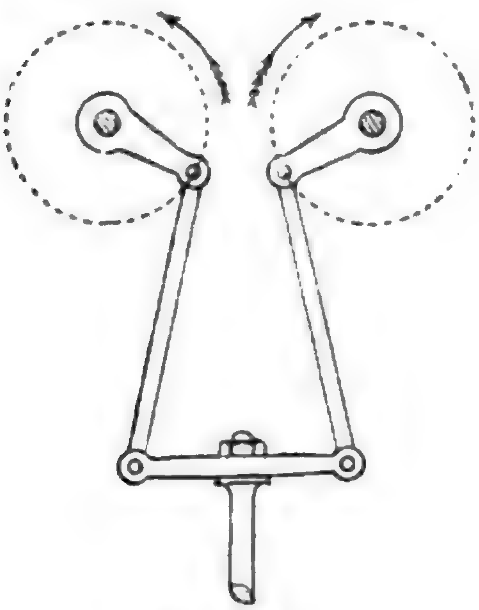


FIG. 479.

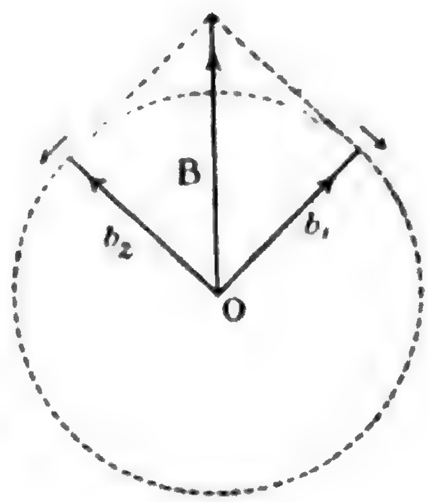


FIG. 480.

of the circular motions. Ferraris deals, however, with the problems of the alternating magnetic field quite generally, applying the geometrical notion of rotating vectors.

If we represent by the vector b_1 which rotates clockwise uniformly about O, the magnitude and direction of a rotating magnetic field, and by b_2 the magnitude and direction of another field of the same strength rotating in the opposite sense with the same frequency n, it will be seen that the direction of the resultant field is always along the line B, and the magnitude of the resultant field will alternate between the

[1] Galileo Ferraris, "A Method for the Treatment of Rotating or Alternating Vectors, with an Application to Alternate-current Motors," *Electrician*, 110, 129, 152, 184, 1894.

values $+ 2b$ and $- 2b$ following a sine function of the time, so that we may write $B = 2 b \sin 2 \pi n t$.

Conversely, if we have an alternating field following the law $B_0 \sin 2 \pi n t$ as in a monophase motor, we may resolve it into two oppositely rotating fields of the same frequency n, and consider the effect of each field separately upon the rotor.

If the rotor turns clockwise with a frequency m, the frequency of rotation of the clockwise field with respect to the rotor will be $n - m$, and the frequency of rotation of the counter-clockwise field with respect to the rotor will be $n + m$.

Each field may be considered as generating currents in the rotor, and the torque due to such currents flowing through conductors in the field may be ascertained by the formulæ employed in the case of rotary-field motors.

Now it was found above (see p. 682) that a field rotating with a speed s relatively to the rotor produced a torque

$$T = q \frac{r s}{r^2 + 4 \pi^2 L^2 s^2},$$

where $L = k$, and the coefficient 2π is added because on p. 682 s was an angular speed, whereas here n and m are revelutions per second.

The torque due to the two oppositely rotating fields will be

$$\text{Torque} = q r \left[\frac{n - m}{r^2 + 4 \pi^2 L^2 (n - m)^2} - \frac{n + m}{r^2 + 4 \pi^2 L^2 (n + m)^2} \right],$$

where q is proportional to the number of conductors on the rotor and to the square of the magnetic flux.

It is not necessary to consider the partial torque exerted by the currents due to one rotating field flowing in conductors that are immersed in the *oppositely* rotating field, because the frequency of these currents differs by $2 m$ from the frequency of that opposite field; and consequently this torque is rapidly reversing in direction.

In order to find the torque due to the field rotating clockwise with the frequency $n - m$, we draw the curve O P Q W

(Fig. 481) (see p. 683 where the curve is reversed) showing the relation between slip and torque obtained by the formula

$$T = q \frac{r s}{r^2 + 4 \pi^2 L^2 s^2}.$$

Let $O Q_{,}$ represent the speed of rotation of field of frequency n; then measuring backwards from $Q_{,}$ a distance $Q_{,} P_{,} = m$ (= speed of rotor) we get the abscissa $O P_{,} = n - m$, and the ordinate $P_{,} P$ represents the torque in question.

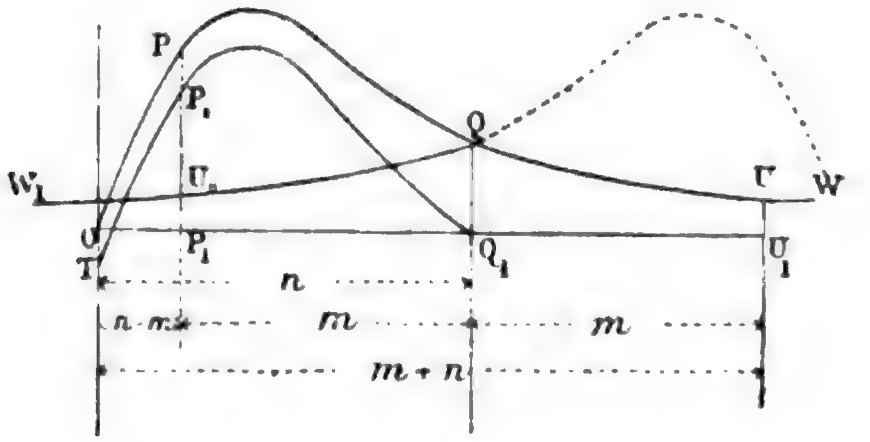


FIG. 481.

To find the torque due to the counter-clockwise rotating field, we measure off forwards from $Q_{,}$ the distance $Q_{,} U_{,} = m$ and get $O U_{,} = n + m$, then $U U_{,}$ represents the torque due to a slip $n + m$. This being in the opposite sense to the torque $P P_{,}$ we can cut off from $P P_{,}$ a part $P P_{,,} = U U_{,}$, and obtain $P_{,,} P_{,}$ which represents the actual torque on the rotor. For convenience in subtracting the torques due to counter-clockwise field we may draw $Q W_{,}$ symmetrical with $Q W$, and then subtract the intercepted parts such as $U_{,,} P_{,}$ from the ordinates such as $P P_{,}$. Doing this for all the ordinates between O and $Q_{,}$ we obtain the new curve $T P_{,,} Q_{,}$, the ordinates of which represent the actual torque for various values of m. When $m = 0$, that is to say, when the rotor is stationary, the two opposite torques balance one another; as m is increased the torque rises to a maximum, and then falls to zero before m is quite as great as n. Any further increase in m produces an opposing torque.

This argument assumes that the impressed flux remains

fixed, which is only true so long as the motor is supplied with the same current. The curve cannot therefore be taken as the true characteristic of the monophase motor supplied at constant voltage, but is useful as a simple indication of its general behaviour. When load is thrown on to the motor its speed decreases a little, more current flows through the stator, and the impressed field is correspondingly increased, so that the quantity denoted by q increases in reality with the load.

A number of alternate-current motors have been devised which do not come under any one of the preceding classes, and yet are hardly susceptible of classification.

Laminated Series Motors.—For small power an ordinary continuous-current motor with commutator and brushes may be used, provided the field-magnet is built of laminated iron.

Retarded Field Motors.—If one end of a laminated bar of iron is placed in a magnetizing coil supplied with an alternate current, it will undergo an alternating magnetization. But if at a point further along it is surrounded by a stout copper ring or ferrule, the eddy-currents induced in the latter, being out of phase with the primary current, will react locally on the alternating magnetization, and retard the phase of the magnetic polarity at all points beyond. Consequently, if two or three such closed rings or bands of copper surround the iron core at different distances along (Fig. 482), the effect will be the same as if the poles travelled along the iron at a finite speed, a north pole being followed by a south pole, and again by a north pole, each travelling toward the tip, and there dying out. On this plan the Ferranti-Wright motor is based. It is used in Ferranti's alternate-current meters. A pivoted iron disk is placed between two curved pole-pieces of laminated iron, each of which is furnished with retarding-rings of copper.

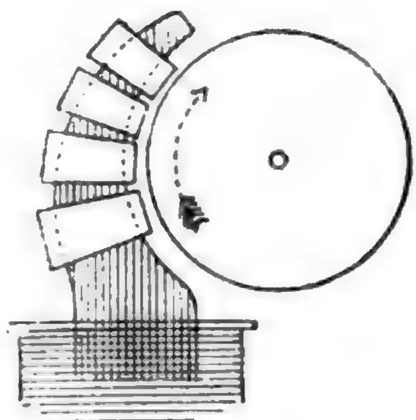


Fig. 482.

CHAPTER XXVI.

TRANSFORMERS.

WHENEVER electric energy is to be transmitted to a distance, considerations of economy dictate that high voltages[1] shall be employed. On the other hand, considerations respecting safety to person as well as those respecting the pressures suitable for lamps, dictate that the voltage at which the energy should be supplied to the consumer should be comparatively low, or from 100 to 200 volts at the most. Hence devices are required which shall receive the currents at high pressure from the feeders or main lines, and shall transform the energy so as to give out larger currents at lower pressures. Such devices are called *transformers*. Notes on the history of transformers were given in the previous edition of this work.

[1] This is fully explained in Chapter XXVIII. on Transmission of Energy, but may be briefly recapitulated here. It must be remembered that the energy supplied per second is the product of two factors, the current and the pressure at which that current is supplied, or in our notation,

$$\mathcal{E}\, C = \text{electric energy per second (in } \textit{watts}\text{)}.$$

The magnitudes of the two factors may vary, but the value of the power supplied depends only on the product of the two; for example, the energy furnished per second by a current of 10 amperes supplied at a pressure of 2000 volts is exactly the same in amount as that furnished per second by a current of 400 amperes supplied at a pressure of 50 volts; in each case the product is 20,000 watts. Now the loss of energy that occurs in transmission through a well-insulated wire depends also on two factors, the current and the resistance of the wire, and in a given wire is proportional to the square of the current. In the above example the current of 400 amperes, if transmitted through the same wire as the 10-ampere current, would, because it is forty times as great, waste sixteen hundred times as much energy in heating the wire. Or, to put it the other way round, for the same loss of energy one may use, to carry the 10-ampere current at 2000 volts, a wire having only $\frac{1}{1600}$th of the sectional area of the wire used for the 400-ampere current at 50 volts. The cost of copper conductors for the distributing lines is therefore very greatly economised by employing high pressures, and using step-down transformers to reduce the pressure to that needed for the lamps.

For transforming continuous currents a revolving apparatus is required consisting, in principle, of a motor (driven by the incoming or primary current) driving a generator, which induces a secondary current at the desired (low) pressure. Such combinations, known as *motor-generators*, are specially considered in the next chapter.

For transforming alternating currents (whether single-phase or polyphase) all that is needed is a stationary apparatus consisting of a suitable core of laminated iron with primary and secondary coils wound upon it—in fact an induction coil. These *alternate-current transformers* form the subject of the present chapter.

General Notions about Alternate-current Transformers.

The simplest and earliest form of transformer was the iron ring of Faraday, Fig. 483, upon which he wound two coils, a

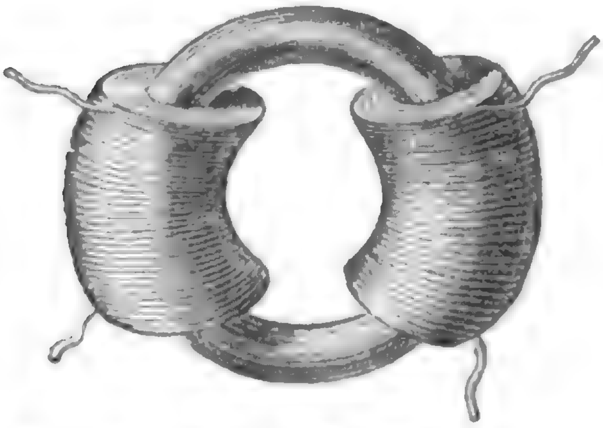


Fig. 483.—Faraday's Ring, with Primary and Secondary Coils.

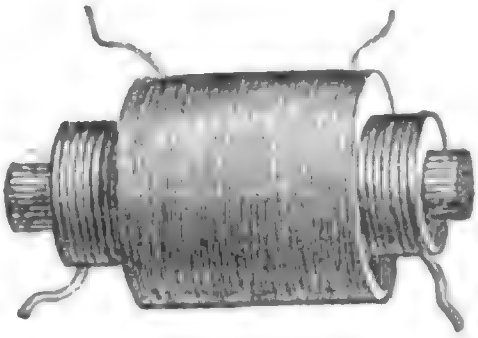


Fig. 484.—Simple Induction Coil, with Straight Core.

primary and a secondary. In elementary treatises on electricity it is explained how an electromotive-force is induced in the secondary whenever the primary current is increasing or diminishing, because the magnetic lines made in the iron core by the primary current thread through the secondary coil and act inductively. The same thing occurs in the form shown in Fig. 484, where the two coils are wound one outside the other upon a straight core of iron wires.

An alternating transformer may be regarded as a species of dynamo, in which neither armature nor field-magnet revolve, but in which the magnetism of the iron circuit is made to vary through rapidly repeated cycles of alternation, by separately exciting it with an alternating current. The primary coil of the transformer corresponds to the field-magnet coil of the dynamo; the secondary of the transformer to the armature coil of the dynamo.

If an alternating current having a frequency of n periods per second be sent into either of the coils there will be set up in the other coil an alternating electromotive-force having the same frequency, because the iron core is undergoing an alternating magnetization also of n cycles per second. The effect on the second circuit is the same as if the magnetized iron core were being plunged into and removed from the second coil n times per second.

Our first step shall then be to calculate the electromotive-force induced in a coil of any given number of turns by an alternating magnetic flux in the core within it. Let S be the number of spirals or turns in the coil, and N the maximum value of the flux in the core. Suppose that the changes of the flux follow a sine law we may then write for the value of the flux at time t after the maximum has occurred,

$$\mathrm{N}_t = \mathrm{N} \cos 2 \pi n t.$$

But the electromotive-force in any one turn is proportional to the rate at which N is changing, or to $d \mathrm{N} / d t$. Further, we must multiply by S, and divide by 10^8 to bring to volts. Performing the differentiation we get

$$\mathrm{E}_t = 2 \pi n \mathrm{S} \mathrm{N} \sin 2 \pi n t \div 10^8.$$

The virtual value of this electromotive-force is obtained by substituting for $\sin 2 \pi n t$ its square-root-of-mean-square value namely $\sqrt{2}$, giving us

$$\mathrm{E} = 4{\cdot}45 \, n \mathrm{S} \mathrm{N} \div 10^8.$$

This formula is fundamental in transformer calculations.

Now consider a simple magnetic circuit, having wound on it a primary coil of S_1 turns, and a secondary coil of S_2 turns. We may conceive it like Fig. 485; but to avoid complications at first, we will suppose that there is no magnetic leakage, that is to say, all the magnetic lines created by the current in the primary coil thread through the secondary coil. The impressed electromotive-force applied to the terminals of the primary coil sets up a primary current which produces an alternating magnetic flux, and this alternating flux in turn induces electromotive-forces, not only in the secondary coil but also a back-electromotive-force in the primary. These two induced electromotive-forces will be strictly proportional to the respective numbers of turns, and absolutely in phase with one another. We may write them

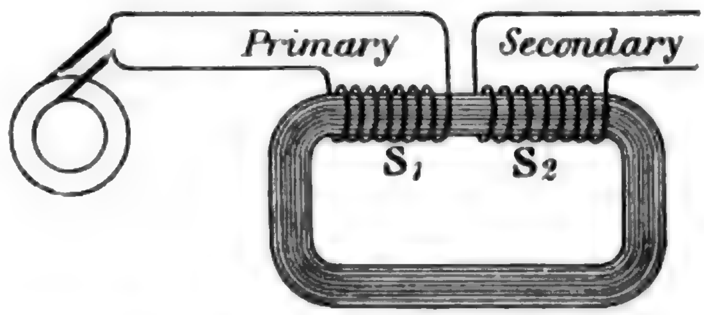


FIG. 485.—ELEMENTARY TRANSFORMER.

$$E_1 = 4{\cdot}45\, n\, S_1 \mathrm{N} \div 10^8,$$
$$E_2 = 4{\cdot}45\, n\, S_2 \mathrm{N} \div 10^8;$$

we have, therefore,

$$\frac{E_1}{E_2} = \frac{S_1}{S_2}.$$

This ratio is called the *ratio of transformation*, and is in this chapter denoted by k.

Two main cases now arise for consideration: (i.) when the secondary circuit is open; (ii.) when the secondary circuit is closed on a load of lamps or other resistance.

If the secondary circuit is open, though electromotive-force may be induced in it there will be no secondary current, and therefore no reaction of any kind due to this coil. It might as well be absent. The only reaction will be that of the primary coil on itself. As in a motor running light, so in the transformer at no load, the back-electromotive-force will be almost equal to the impressed electromotive-

force. The latter must be slightly greater, for there must be enough volts unbalanced to drive the requisite small magnetizing current through the internal resistance of the primary coils; as there are hysteresis and eddy-current losses they also must be provided for by a small additional primary current. But, save for these, the whole action of the primary, when the secondary is open, is that of a *choking coil*, and the induced electromotive-force E_1 will be in almost exactly opposite phase to the primary current.

Now pass to the case where the secondary is closed upon a load of lamps or other resistance. We will suppose this resistance to be for the present a simple non-inductive resistance. There will be a secondary current in phase with the induced electromotive-force E_2, therefore in phase also with E_1, therefore in almost exact opposition of phase to the primary current. When the primary is rising to its maximum, the secondary will also be rising to its maximum, but flowing the opposite way round. While the primary is magnetizing the secondary is demagnetizing; and it is clear that the magnetic flux, on which the counter-electromotive force in the primary depends, cannot be as great as before unless more current flows from the primary source. In fact, more current will of itself flow in the primary because of the demagnetizing effect of the secondary current. The effect of the presence of the current in the second circuit is then to *unchoke* the primary. The primary coil now acts not as a choking coil to dam back the primary current, but as a *working* coil, inducing current in the secondary by flowing sufficiently strongly to keep up the alternating magnetic flux in spite of the demagnetizing tendency of the secondary current. If only half the lamps are on, then the primary will act partly as a choking coil and partly as a working coil. If the primary impressed volts are kept constant, the secondary volts at the terminals of the lamp circuit will be nearly constant also; and the apparatus becomes beautifully self-regulating, more current flowing into the primary of itself when more lamps are turned on in the secondary circuit.

The elementary theory of this simple case of a trans-

former without leakage, working on a non-inductive load of lamps, is quite easy. Adopting the same notation as used for motors and dynamos, write $\mathcal{E}$ for the volts of supply as measured at the primary terminals, and e as the volts at the secondary terminals. Let r_1 be the internal resistance of the primary and r_2 that of the secondary. Call the ratio of transformation $k = S_1 / S_2 = E_1 / E_2$. Since (apart from small hysteresis losses, here neglected) the work done *by* the fluctuating magnetism of the core is equal to the work done *on* it, we may further write $E_1 C_1 = E_2 C_2$; whence it follows that $C_1 = C_2 / k$. The volts lost in the primar yare $r_1 C_1$; those in the secondary $r_2 C_2$. Hence we may write

$$\mathcal{E} = E_1 + r_1 C_1,$$
$$e = E_2 - r_2 C_2.$$

Writing the first of these as:

$$E_1 = \mathcal{E} - r_1 C_1 = \mathcal{E} - r_1 C_2 / k,$$

and inserting E_1 / k for E_2 in the second equation, and substituting, we get

$$e = \frac{\mathcal{E}}{k} - \left(\frac{r_1}{k^2} + r_2\right) C_2;$$

which shows that everything goes on in the secondary as though the primary had been removed, and we had substituted for $\mathcal{E}$ a portion of it proportional to the number of windings, and at the same time had added to the internal resistance an amount equal to the internal resistance of the primary reduced in proportion to the square of the number of windings.

Example.—In a Mordey $1\frac{1}{2}$ kilowatt transformer, $S_1 = 300$; $S_2 = 12$; $r_1 = 10$ ohms; $r_2 = 0{\cdot}014$ ohm; $\mathcal{E} = 1000$; find e when $C_2 = 36$ amperes. Here $k = 25$, so that on open circuit the secondary volts would be exactly $\frac{1}{25}$ of the primary volts, or 40 volts. But working out by the formula for the output of 36 amperes the terminal volts e drop to $38{\cdot}92$.

Construction of Transformers.

The function of the core is to carry the magnetic lines that are created by the circulation of surrounding currents, and to excite inductive actions in those coils. It is therefore obvious that in the construction of a transformer the core must have a sufficiently great sectional area; further, that its shape ought to be such that all the magnetic lines created by the primary coil shall pass without leakage through the aperture of the secondary coil; and to accomplish this the magnetic circuit ought to be a closed circuit of compact form, and with as few joints as possible. If there is magnetic leakage, so that some of the lines made by the currents in one of the coils do not thread through the other coil, then each coil will tend partially to choke its own currents, and the drop in volts at full load will be greater than that which results (as above) merely from internal resistances.[1] To avoid inductive drop then, we must use such a construction that there is a minimum tendency to magnetic leakage. It is also important to keep the form of the magnetic circuit as compact as possible, so that the necessary magnetic flux may be attained with as few ampere-turns as possible. If by avoiding joints and gaps in the magnetic circuit, by using the most permeable iron, by having the length of path along the circuit as short as may be, and by having a sufficient cross-section of iron, the magnetic reluctance is kept low, then a very small magnetizing current will be needed. This is of great importance in all transformers that are to be used for light all-day loads.

For high-efficiency transformers it is also necessary to avoid those kinds of iron that have much hysteresis (p. 137), and to use sheets so thin (about 0·5 millimetre or $\frac{1}{50}$ inch is the usual limit) that eddy-current losses are kept small.

[1] Another way of stating this result is as follows:—As will be shown at the end of this chapter, the effect of there being a coefficient of mutual induction between two circuits, is to diminish the self-induction of each of them separately; or if their convolutions are wound around the same core, in geometrically identical relations, the effect of the mutual induction is to wipe out the separate self-inductions. Any unbalanced self-induction in either circuit will necessarily tend to make that circuit act as a choking-coil; and any magnetic leakage will act as an unbalanced self-induction.

As a further constructional point it is not unimportant to choose such forms as will permit the coils to be wound in a lathe, and to be mounted and dismounted without undue labour.

Return now to Fig. 483 which depicts Faraday's ring-transformer. Its iron core was not laminated; and the placing of the two coils was such that there was a great tendency to magnetic leakage across the ring from top to bottom. Two obvious improvements are (1) to make the core of wire or washers; (2) to wind the primary and secondary coils in sections, sandwiched between one another, as in Fig. 486.

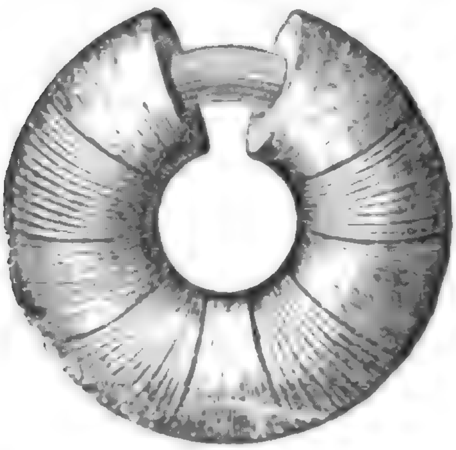


FIG. 486.—RING TRANSFORMER, WITH SANDWICHED COILS.

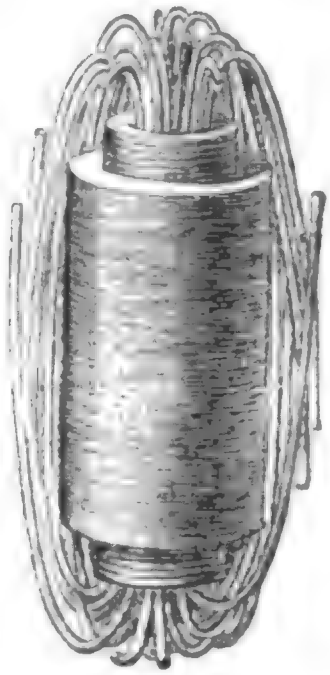


FIG. 487.—VARLEY'S CLOSED-CIRCUIT TRANSFORMER.

Now turn to Fig. 484, p. 695, which depicts the cylindrical type of induction coil, also used by Faraday, further developed by Callan, Masson and Ritchie, and perfected for spark purposes by Ruhmkorff. It has a bad magnetic circuit; for the magnetic lines will have to find their return paths through the surrounding air: it will take a relatively large magnetizing current, and there will be some leakage, though not quite as much as if the two coils had been wound separately on the two ends of the core instead of over one another. Fig. 487 depicts a form due to Varley, which is an obvious improvement, the magnetic circuit being much better closed. The

modern Pyke and Salomons transformer is like this, but has the coils sandwiched along the core. The Ferranti transformer, Fig. 499, also resembles this form, but has its core of ribbons of sheet iron. If we imagine the two coils made quite short and set side by side on the core, the elongated form of Fig. 487 might be reduced to the squat shape of Fig. 488, which is a form introduced by Zipernowsky. The primary and secondary coils are first laid upon one another, and the iron core is then wound through and over them by a shuttle, so that the whole of the copper is enclosed within the iron. In the drawing (Fig. 488), the front portion of the iron winding is represented as removed to show the interior. Mr. Kapp has proposed the name of "shell-transformers" for this type of apparatus as distinguished from those with a mere straight or a non-expanded internal core, which he calls "core-transformers." But the two types run into one another. All shell-transformers have a core, and all core-transformers, if they have closed magnetic circuits at all, have some portion of iron returning outside the windings; so it is only a question of detail how far this return portion is spread out as a shell. It is certain that excellent transformers are made in accordance with both extremes of type.

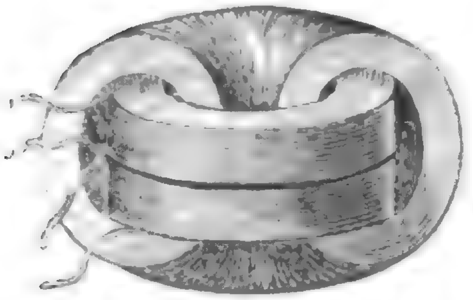
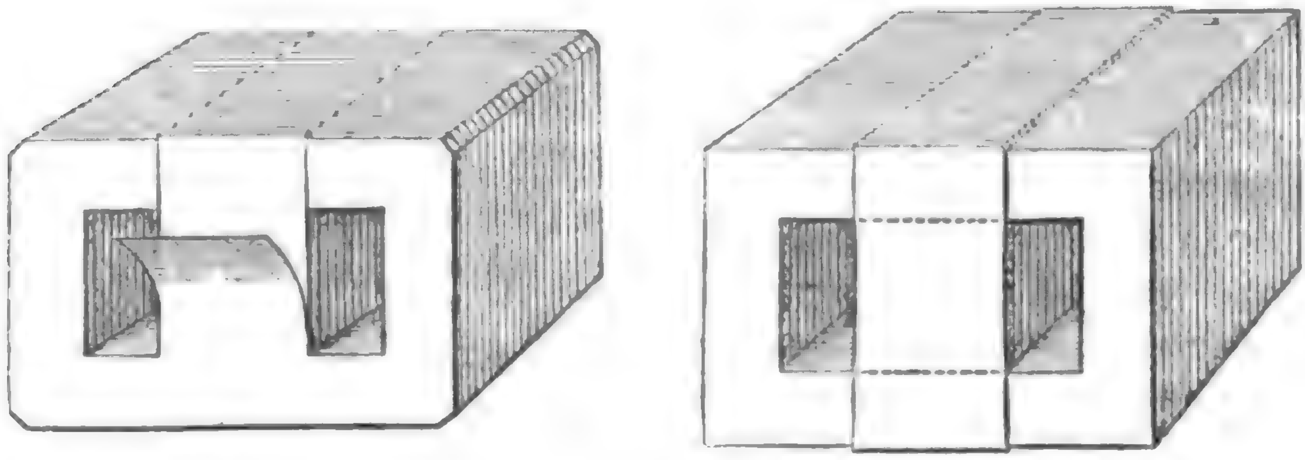


FIG. 488.—ZIPERNOWSKY'S SHELL-TRANSFORMER.

Types of Modern Transformers.—Modern transformers, almost without exception, have cores built up of thin sheet stampings. The forms shown in Figs. 489 and 490 are typical of a class in which the stampings when assembled constitute a long central core and an external shell, with two long apertures to receive the coils. Different firms build up the stampings differently, and wind the coils in different ways.

To avoid waste of material Mordey introduced the method shown in Fig. 490, where the cross-pieces that form the core are simply the rectangular portions stamped out of the external plates that form the shell. If the external dimensions of the

shell-plate are 6 by 4 inches, the core-plates will be 4 by 2 inches, and each of the windows will be 2 by 1 inches. These pieces are interlaced as shown, being built up, however,



FIGS. 489 and 490.—CORE-PLATES OF TRANSFORMERS (Westinghouse and Mordey).

around the coils (not shown in Fig. 490) which are previously wound upon a light rectangular former A, Fig. 491, made of hard wood steeped in ozokerit.

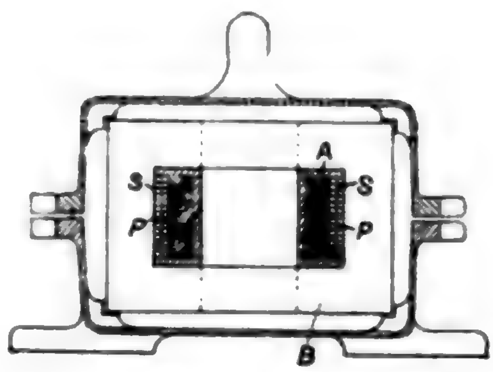


FIG. 491.
MORDEY'S TRANSFORMER
(Transverse Section).

Fig. 492 shows in diagram four different ways of disposing the primary and secondary windings in the space available in the apertures. Apart from an allowance for the small extra amount of primary current for magnetizing, the quantities of copper needed for primary and secondary are equal (for minimum heat-waste and drop); for if the secondary wire has only $\frac{1}{k}$ as many turns as the primary it will have to carry k times as much current, and therefore require a section k times as great. It is usual to make the primary of a round wire well insulated, and the secondary of insulated copper ribbon or rectangular strip. And as the insulation of the fine primary wire takes up a relatively greater space, the total space left for the primary is greater than that for the secondary. Owing to the conditions of imperfect ventilation a high amperage cannot

be used; a current-density of 500 amperes per square inch being considered rather high. (Refer to table, p. 371).

In Figs. 493, 494 and 495 are depicted, without showing the jointing of the cores, three types of construction now most in vogue. The first of these is the long shell type just discussed; with its exceedingly compact magnetic circuit and its elongated coils built on a special frame. The second represents a type used by the Oerlikon Co. (compare Fig. 496) having a long core over which the coils, wound in cylindrical shapes on bobbins, can be slipped, the shell-yokes being then added, being furnished with faced joints. This feature of placing the windings cylindrically over one another upon a long core is found excellent for avoiding leakage and inductive drop, and it therefore gives good regulation. As will be noticed, an approximation to cylindrical form is procured by

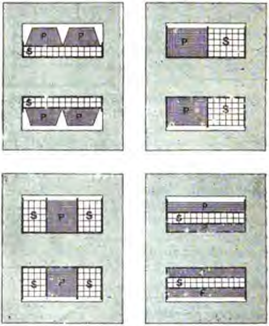


FIG. 492.—VARIOUS MODES OF DISPOSING TRANSFORMER WINDINGS.

use of graduated sizes of core-plates. The fine-wire high-voltage winding is divided into two parts for the purpose of keeping far apart the portions which differ greatly in potential; and the winding is coned at its ends so as to obviate the use of bobbin cheeks; insulation in oil or air being better without them than with them.

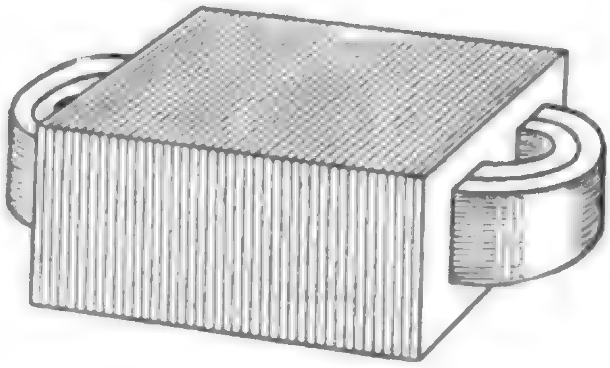


FIG. 493.

The transformer now built by Brown, Boveri & Co. has a similar internal core, over which, on a paper cylinder, is slipped the secondary winding of copper strips, and over this again the primary winding in two coned coils: but the yoke part is not in two portions as in Fig. 496, but in one of double section fitting by faced joints.

The form represented in Fig. 495 is that adopted by Messrs Johnson and Phillips, originally from the designs of

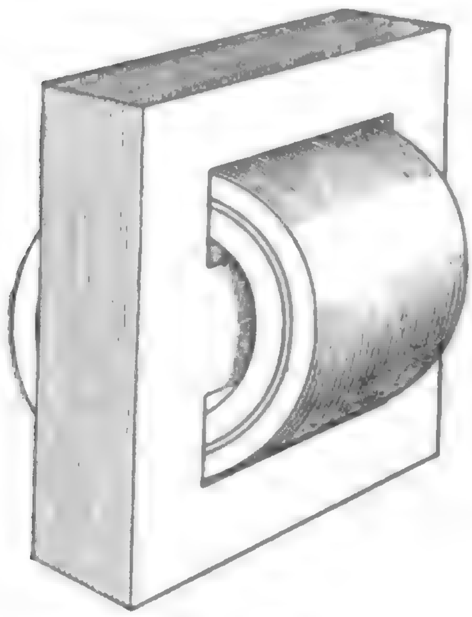


FIG. 494.

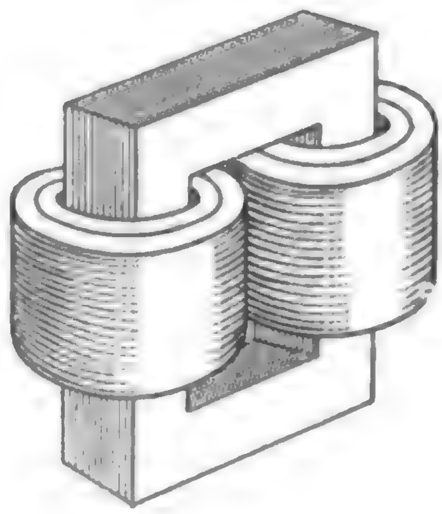


FIG. 495.

Mr. Kapp, and may be described as an improved Faraday ring. Dobrowolsky employs a kindred pattern. Plate XIX. gives drawings, the material for which was principally furnished by Messrs. Johnson and Phillips, who have patented several improvements. The cores as shown in that plate are built up of varnished plates of graduated

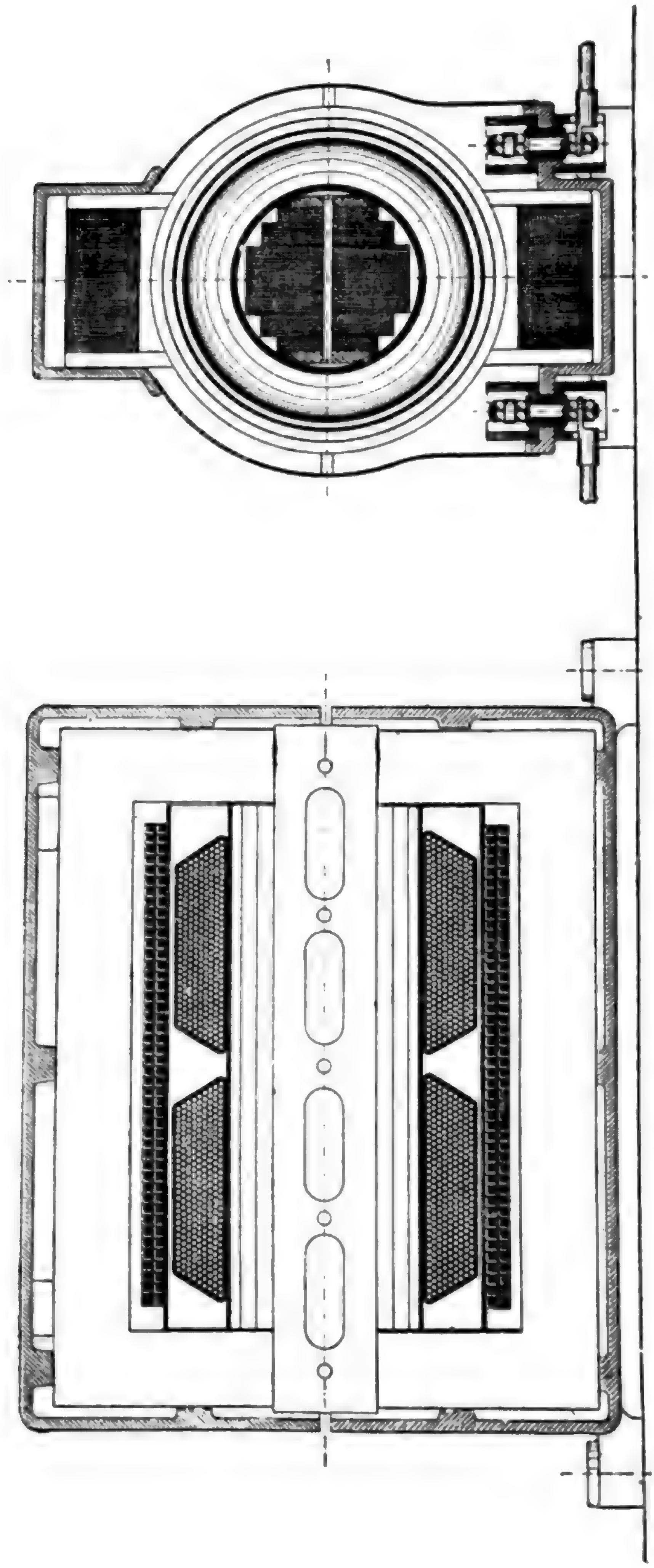


FIG. 496.—OERLIKON CO.'S 20-KILOWATT TRANSFORMER.

sizes, so that the section of each limb is approximately octagonal. The cores are served with tape and coated with shellac varnish. The stampings are in rectangular strips imbricated at the joints, and secured by insulated bolts. Sleeves of insulating material receive the coils, which being cylindrical are slipped over one another on the longer limbs of the core. Afterwards when placed concentrically on the core, sheet ebonite is interposed between them; the fine-wire primary lying outside the secondary. A cast-iron watertight case encloses the whole.

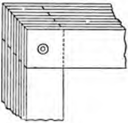


FIG. 497.
IMBRICATED JOINTS.

Fig. 498 illustrates the so-called "Hedgehog" transformer of Swinburne,[1] having as core a bundle of iron wires which, after receiving the copper coils, are spread out at their ends so as to reduce the magnetic reluctance, which is in any case great, the magnetic circuit being an open one. It was supposed to be more efficient, as the weight of iron is so small, reducing the eddy-current and hysteresis losses. But owing to its incomplete magnetic circuit it requires a very large magnetizing current, and therefore at low loads wastes a disproportionate amount of energy in the primary mains. It is now generally agreed that closed-circuit forms are preferable: they have the further advantage of an entire absence of waste from eddy-currents in the copper conductors, however massive.


FIG. 498.
SWINBURNE'S HEDGEHOG TRANSFORMER.

Ferranti's transformer (Fig. 499) for extra high pressure work, has a core made of a large number of thin strips of iron, which pass vertically up through the middle of the copper coils, and

---

[1] *Journal Inst. Electr. Engineers*, xx. 183, 1891.

are bent round below and above on each side, and interlapped so as to complete the magnetic circuit. The coils are made of copper strip, very carefully insulated, and compacted together in sections by insulating material. There are three coils thus built up, the innermost being a portion of the primary, outside this the secondary, and outside this again the rest of the primary. Sheets of ebonite are interposed in the spaces between these coils, so as to prevent sparking across from the high-pressure coils. There is also room for air ventilation in the vertical spaces where these sheets of ebonite are wrapped round between the three piles of coils.

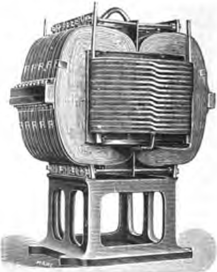


FIG. 499.—FERRANTI'S TRANSFORMER.

Phase-relations in Transformers.—Keeping in mind always as the chief consideration in the operation of a transformer, the alternating magnetic flux in the core, we must next study the relations to it of the other quantities. It may be remarked that in a system of supply at constant voltage, this flux scarcely varies between no load and full load. As in a compounded dynamo, so in a regulated trans-

former, to keep the volts at the terminals of the lamp-circuit constant needs at full load an increase of but 2 or 3 per cent. in the magnetic flux to compensate for the drop. To simplify matters we will suppose, however, that a drop is allowed to occur, but that the flux always alternates around the same cycle. Also, for simplification, suppose the ratio of transformation to be = 1, so that ampere-turns in each coil may be plotted to same scale as amperes. For any other ratio it will at any time be easy to substitute any given value of the ratio k. Then $E_1 = E_2$, and both are at right angles to the line N O N, Fig. 500, which on the clock diagram represents the time when the flux is at its maximum in either direction. Consider first the case of no load; then the only current will be that in the primary, and if there were neither hysteresis nor eddy-currents in the core it would be an entirely wattless current, in quadrature with the primary impressed volts, but in phase with flux. Let the value of this *magnetizing current* C_m be represented by the line O C_m. But as hysteresis and eddy-currents put a small load upon the transformer there will necessarily be a small component of current C_p in phase with the volts. This may be represented by the line O C_p. The actual no-load current will be the resultant of O C_m and O C_p, namely O C_o. The *power factor* at no load will be the ratio of the true watts to the apparent watts, or is $C_p \div C_o$. To furnish the small electromotive-force O v requisite to drive the current C_o through internal resistance of the primary, the impressed primary volts must have a magnitude and phase, such that O $\mathcal{E}$ shall be the resultant of O E_1 and O v. But as the no-load current is, say, only 3 per cent. of the full current, and as the primary lost volts at full load will not be more than 2 per cent., O v will not be more than about $\frac{1}{1500}$ of O E_1, and the difference of phase between O $\mathcal{E}$ and O E_1 will be insignificant.

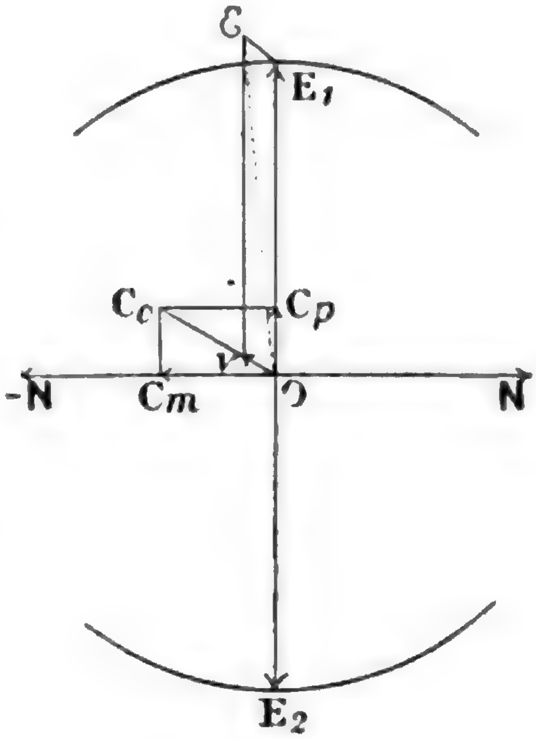


FIG. 500.

At full load the phase relations are somewhat different, and they differ according to whether the load on the secondary circuit is a plain resistance, or as to whether it is inductive, causing a lag of the

secondary current behind E_2. If we consider the latter case it will be easy to see what difference the absence of self-induction would make. As before, take for reference the phase of the flux, and work backwards to find the relative phase of the impressed primary volts. The secondary induced electromotive-force E_2 will, as before, be at right angles to N O N.

Now, if there is inductance in the secondary, as well as resistance, there will (see p. 563) be a lag such that $\tan \phi = p L_2 \div R_2$; and the effective volts $R_2 C_2$, that drive the secondary current through the resistance, will be got by the construction in the lower part of Fig. 501. The length O C_2 may be taken as the effective secondary volts; and the actual volts at terminals e might be found by deducting from O C_2 a short length to represent the lost volts $r_2 C_2$. The secondary current also will be represented in phase by O C_2, and by a suitable change of scale O C_2 might also represent it in magnitude. Producing O C_2 backward to an equal length, and compounding this line with O C_0 (the no-load current) we get O C_1 to represent, according to scale chosen, either the primary current or the primary ampere-turns. Along the same line we take the part O v to represent the volts needed to drive this current through the mere resistance of the primary windings. We shall now have to compound O v with the counter electromotive-force O E_1 induced in the primary by the core; and at the same time we must take into account the unbalanced self-induction in the primary (if any) by drawing a line $x \mathcal{E}$ ($= p L_1 C_1$) at right angles to O C_1. This gives as the final resultant, showing required magnitude and phase of the impressed primary volts, the line O $\mathcal{E}$. Consideration of the diagram will show that the smaller the no-load current the more nearly would C_1 and C_2 be in complete opposition of phase; also that self-induction in the primary throws the phase of E_1 behind $\mathcal{E}$, and that self-induction

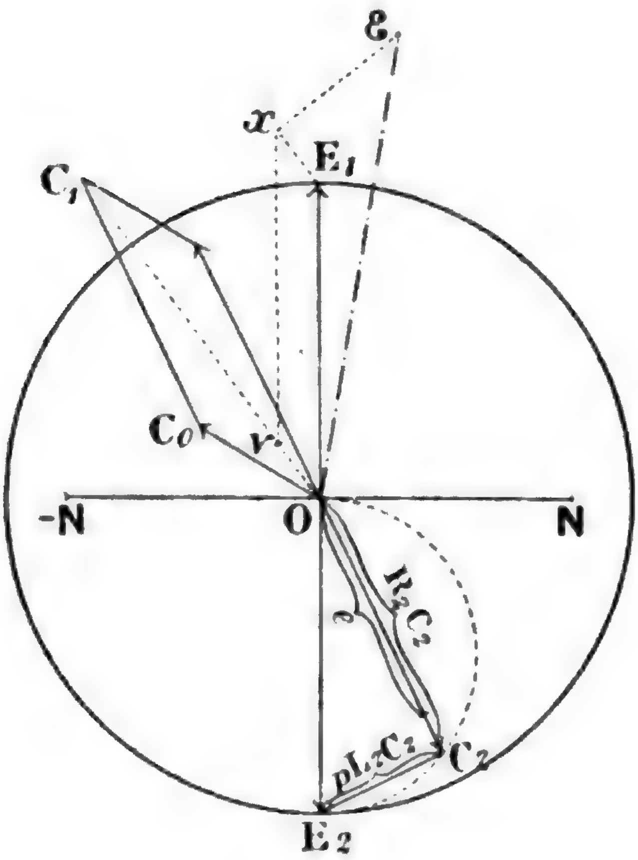


FIG. 501.

in the secondary throws C_2 behind E_2, hence leakage, which throws self-induction into both circuits, tends to shift the lines O $\mathfrak{B}$ and O C_2 nearer to one another.

The actual performance of transformers has been carefully examined by Prof. H. J. Ryan,[1] who has plotted out curves to show the forms and phases of the several varying quantities. The transformer used was a small one of 600 watts capacity, adapted for transforming down from 1000 to 50 volts, the number of windings being 675 in the primary, and 35 in the secondary coil. The volume of laminated iron was about 2050 cubic cm. The mean length of the magnetic circuit was 30·8 cm. and mean cross section

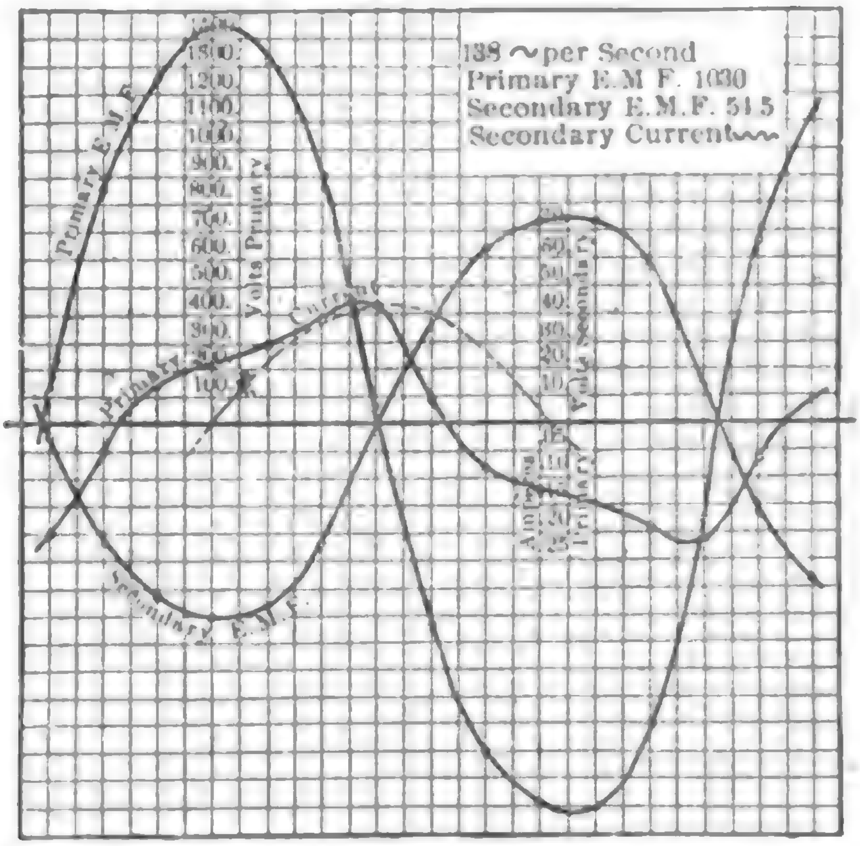


FIG. 502.—TRANSFORMER CURVES ON OPEN CIRCUIT.

63·3 sq. cm.; the frequency used was 138. Figs. 502, 503 and 504 show the results. It will be noted that although the primary current curve differs widely from a curve of sines (especially at light loads), nevertheless the curve of secondary volts is much more nearly like a sine curve; and it is always in almost exact opposition of phase to the curve of primary volts.

[1] *Amer. Inst. Electrical Engineers*, 1889 and 1890. See also *Electrical World*, xiv. 419, Dec. 28, 1889, and xvi. 10, July 25, 1890; also *The Electrician*, xxiv. 263, and xxv. 313, 1890; also *La Lumière Électrique*, xxxv. 233, 1890. See also an appendix paper by Messrs. Humphrey and Powell in *Electrical World*, xvi. 11, 1890, and *The Electrician*, xxv. 280, 1890.

In a second paper Ryan shows that the loss of energy by eddy-currents is less when the core is hot than when it is cold. The curious form assumed by the current curve is due solely to the properties of iron. If the impressed primary volts follow a sine law, that of the magnetizing current and of the primary current at low loads will obviously not have the same form unless the permeability were constant. At that stage of things when permeability is increasing with the flux-density (i. e. when **B** is between 1000 and 6000 (see Fig. 92), the current need not increase so fast as to conform to the sine curve; but at the stage when the permeability is decreasing

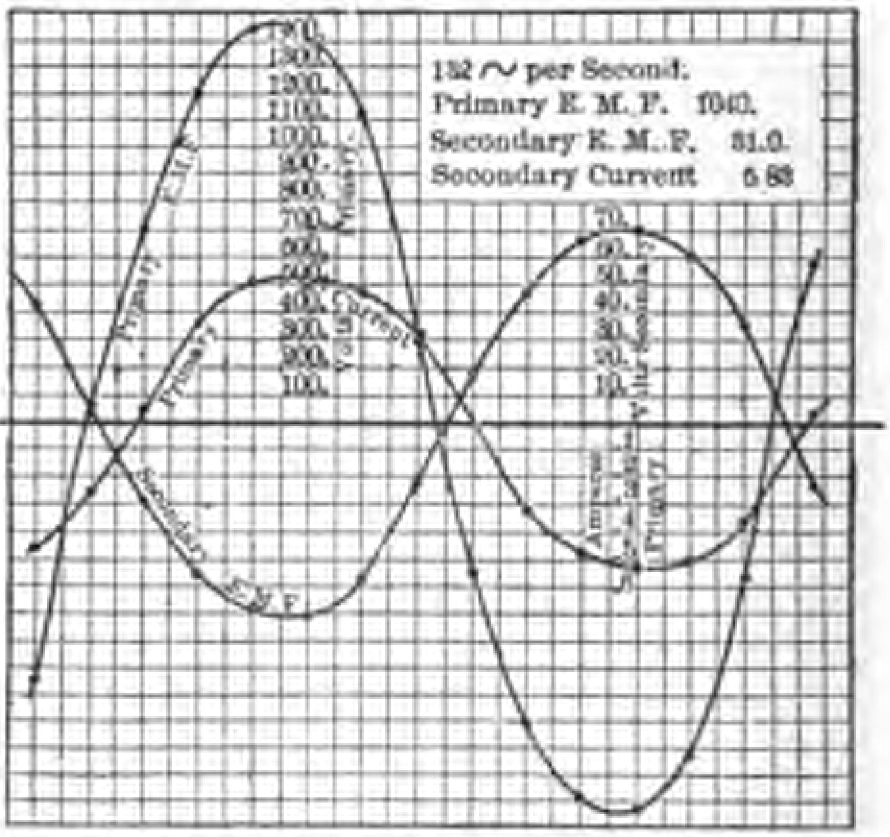


FIG. 503.—TRANSFORMER CURVES AT HALF LOAD.

while **B** is increasing (i. e. when **B** has passed 8000), the current must increase more rapidly than would conform to the sine curve.[1]

Efficiency of Transformers.—It has been found independently by Steinmetz, by Fleming and by Wedding that the efficiency of a given transformer depends to some extent upon the form of the electromotive-force impressed by the generator, a peaked form giving a higher efficiency, a flat-topped square-shouldered form giving a lower efficiency than a pure sine curve. The reason depends on the

[1] See Ryan and Merritt, Fortenbaugh and Sawyer, Major Hippisley, *Proc. Roy. Soc.*, 1892, lii. 255; Fleming, "Delineation of Alternating Current Curves," *Electrician*, 1895, xxxiv. 507; Rimington, E. C., "Alternate Current when E.M.F. is of a zig-zag wave type," *Phys. Review*, iii. 100 (1895).

fact that the hysteresis losses increase disproportionately with the higher flux-densities. For, since the value of the volts at any instant depends on the rate of change in the magnetic flux, a square-shouldered volt curve will imply a high-peaked curve of flux-density, and *vice versâ*. Dr. Roessler, in a recent investigation[1] on this subject, found that at no load the primary winding when the volts followed a sine law absorbed 1·5 times as much energy as when a peaked wave was used. He pointed out that one objection to the peaked wave was that it put a greater stress upon the insulation than a sine wave of the same virtual value.

Many discussions have arisen over the curves of transformers and

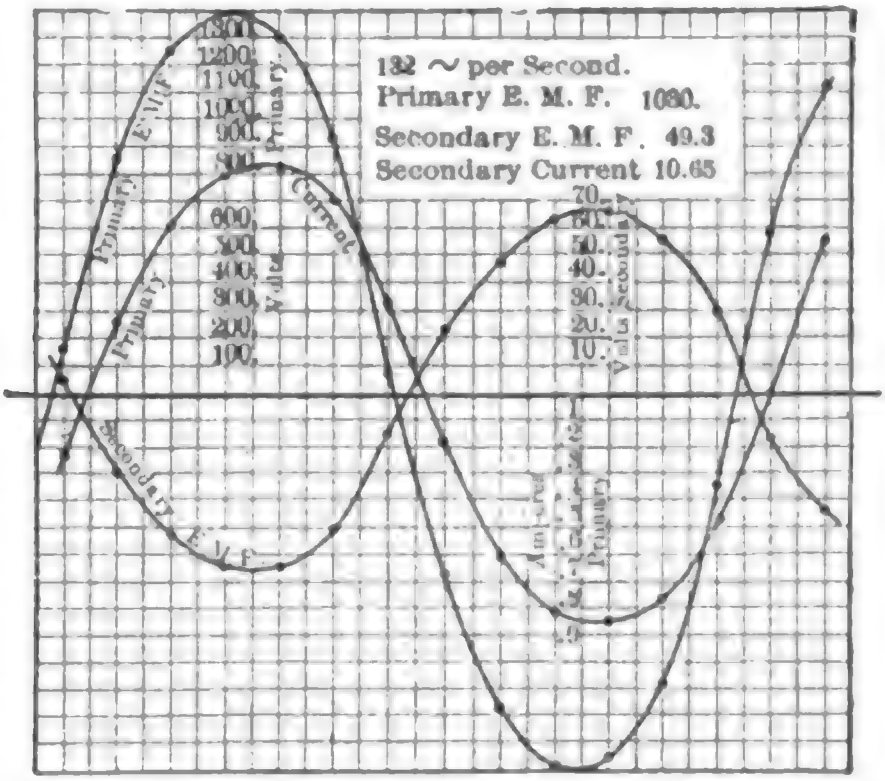


FIG. 504.—TRANSFORMER CURVES AT FULL LOAD.

over the efficiency under various conditions.[2] Fleming[3] in particular has published most valuable determinations of the efficiencies of a large number of transformers. The reader should also consult the writings of Bedell and Crehore, Kapp, Weekes, and Feldmann. The following table gives the principal results of Fleming's tests. The last named on the list had an efficiency of 97 per cent. at full load; and at one-third load had an efficiency of 94·5 when supplied from a Mordey alternator giving a nearly true sine curve, and of 94·9 when supplied from a Thomson-Houston alternator giving a peaked curve.

[1] *Elek. Zeit.*, August 1, 1895; *Engineer*, August 9, 1895. See also Feldmann, *Electrician*, xxxv. 809; also various writers, *ibid.* xxxiii. 497, 511, 523, 528, 580.

[2] See Mordey, *Inst. Elec. Eng.*, xviii. 609, 1890; Ayrton, *ibid.* 664, 1890.

[3] *Inst. of Elec. Eng.*, 1892, xxi. 594; *see* Sumpner, *ibid.* 740.

Transformers.	Full-load Output from Secondary (watts).	Magnetizing Current (amperes).	Primary Volts.	True Power absorbed at no load (watts).	Apparent Power absorbed at no load (watts).	Power Factor.	Iron-loss, in percentage of full load.	Magnetizing Current in percentage of full current.	Total Voltage drop at full load.	Voltage drop due to copper.	Voltage drop due to leakage.	Frequency during test.	Efficiency at full load.
Ferranti (1885 type)	3,750	0·337	2400	540	808	·68	14·6	21·6	..	..	..	83	85·9
,, ,, ...	7,500	0·25	2435	444	600	·74	5·9	8·1	2·6	1·9	·7	83	90·8
,, ,, ...	15,000	0·57	2389	1019	1368	·75	6·8	9·0	..	..	..	83	91·1
,, (1892 type)	11,250	0·076	2400	148	182	·81	1·31	1·61	3·4	2·75	·65	83	95·5
,, ,, ...	15,000	0·112	2400	228	269	·85	1·52	1·79	2·1	1·65	·45	83	96·6
Swinburne (Hedgehog)	3,000	0·74	2400	112	1775	·063	3·73	59·0	3·2	2·23	·97	83	93·5
,, ,, ...	6,000	1·216	2400	165	2920	·05	2·75	47·5	..	..	..	83	96·1
Westinghouse	6,500	0·05	2400	95	120	·79	1·46	1·85	2·4	1·38	1·02	83	96·9
Mordey (Brush Company)	6,000	0·076	2400	140	182	·77	2·33	3·05	1·8	1·75	·05	83	95·4
Thomson-Houston	4,500	0·083	2400	108	199	·54	2·4	4·42	3·3	2·47	·83	83	94·7
Kapp (Johnson and Phillips)	4,000	0·145	2400	152	348	·61	3·8	8·7	1·9	1·83	·07	83	94·2
Mordey (Brush Company)	50,000	0·645	2206	934	1423	·656	1·7	2·4	2·45	2·37	·08	100	97·0

Design of Transformers.

In designing a transformer that shall have a given output when supplied from mains that are operating at a given voltage and frequency, there are several modes of procedure; and in many points experience is the only guide. The following is probably the best way to go to work. First select the type of structure, then from economical considerations decide what will be the permissible loss of power in iron and in copper. If the transformer is for all-day use at low loads the iron loss must at all hazards be kept low. If only for use during short periods a large copper loss may be allowed. If it is for motor running a considerable inductive drop is admissible. Having decided how many watts may be lost in the iron, fix, from previous experience, the approximate dimensions of the ironwork. Choose the size of core stampings, and determine approximately the number likely to be wanted for the output. It will be easy to take a few more or a few less if on completing a first calculation some change seems desirable. Then estimate the approximate weight of iron, and from this and the permissible loss in watts calculate the loss per pound of iron. (This should come out from 0·5 to 1·3 watts.) Then refer to the curve, Fig. 91, which connects this loss with the flux-density **B**, and find the corresponding value of **B**. If this comes out lower than 4000 or higher than 8000, it will be well at once to go back and take less iron or more as the case may be. Having found a reasonable value for **B**, estimate (in sq. centimetres) the nett area of section of the core you have chosen, and multiplying this by **B** you get the flux **N**. Then from **N** and the prescribed voltage and frequency you find S_1 by the formula on p. 697, and from S_1 and the ratio of transformation you find S_2.

At this stage it may be well to calculate the no-load current by finding separately the wattless magnetizing current C_m, and the waste-power current C_p necessitated by hysteresis and eddy-currents. The former may be calculated by magnetic-circuit principles, and the length l of the path of the flux along the magnetic circuit and the value of the permeability μ that corresponds to the particular value of **B**, by the formula

$$C_m = \frac{\mathbf{B}\,l}{\sqrt{2}\,.\,0{\cdot}4\,\pi\,.\,\mu\,.\,S_1} = 0{\cdot}565\,\mathbf{B}\,l \div \mu\,S_1.$$

The waste-power current C_p is calculated from the power permitted to be wasted in the core, by dividing down by the primary volts.

Finally the no-load current C_o is calculated (see Fig. 500) by the formula

$$C_o = \sqrt{C_m^2 + C_p^2}.$$

Returning to the design, calculate from the drawing (with due allowance for layers of insulation) the mean length of one turn of primary winding, of primary, and of secondary. Then from the available space left for the windings (allowing about $\frac{3}{5}$ of this for the primary winding because of insulation requirements, and $\frac{2}{5}$ for the secondary winding) and the numbers S_1 and S_2 calculate the sections, resistances and weights of copper. Then work out the watts lost in copper at full load and no load, and the current density. If the copper losses come too great you have not left winding space enough, and must take a larger iron core. It depends on the type of structure as to what you can do with a larger core. If it is such that the apertures for the windings (as in Fig. 492) are no larger than before, it will, by having a greater section of iron, have the advantage that **N** being greater, S_1 and S_2 may both be smaller, and therefore larger sizes of copper wires can be got into the same apertures. If the new core is longer than the old one, but no thicker, you can use the same numbers of turns as first calculated, but thicker wires.

In all cases it is well to work out on paper the effect of two or three different selections, and to choose that which comes nearest to the prescribed conditions. Some capital examples of working out are given by Evershed.[1]

Another method of procedure is to assume an iron core of given dimensions, and fixing frequency and voltages, to work out the windings to give a definite flux-density (say $\mathbf{B} = 5000$) in the iron ; and take the sections of the two windings as large as is structurally possible. This leaves the currents undetermined, and leaves the rating of the full-load output to be determined either by the limit of permissible temperature-rise (to be found by experiment, or by calculation from losses and surface) or by the voltage drop, or approximately by the current density permissible, or by the limit of efficiency. Some makers rate their transformers above the output at which the rise of temperature will be within safe limits. The final degree to which after some hours' full working the temperature rises depends on the total losses in iron and copper, on the available surface for radiating this heat, and on the facilities for cooling, such for example as the circulation of oil in the outer case. A usual figure of allow-

[1] *The Electrician*, xxvi. p. 477 et seq.

ance of cooling surface is 40 sq. centimetres per watt of loss. At this allowance the temperature rise will be about 50° C. above the surrounding atmosphere if there is no oil cooling, or about 40 degrees with oil in the case. And, within the limits of 15 to 65 sq. centimetres per watt, the temperature rise will vary roughly inversely with the available surface. E. Thomson has suggested the use of perforated secondary conductors to allow of greater cooling surface. The newest Westinghouse transformers have the projecting ends of the sandwiched coils bent away from one another for better ventilation. A forced circulation of oil has been suggested.

If a transformer designed to work at a certain voltage at a given frequency is used for the same voltage at a lower frequency the efficiency will be less: for, from the fundamental formula on p. 696, it is clear that the cycles of magnetization of the iron core must go to higher maxima of flux-density, causing disproportionate losses. If a transformer designed for a 2000-volt circuit at 100 periods is used on a system at 50 periods it ought to be rated at lower voltage, say as a 1000-volt transformer, or else rewound. On the other hand, raising the frequency lowers the flux-density (for the same voltage) and therefore raises the efficiency. If the flux-density is unaltered, the loss per cycle will also be unchanged, and the loss per second will be proportional to the number of cycles per second. Other things being equal it may be taken that for a given copper loss (and therefore for given current) the output is proportional to the voltage, and therefore for a proportional iron loss, is proportional to the frequency. Hence for a given total loss the output of a given transformer is proportional to the frequency. In other words, high frequency means a saving of weight and cost, smaller transformers being used than with low-frequency of supply.

Constant-current Alternating Transformers.

Transformers arranged so that the two self-inductions of the two coils are high compared with the mutual induction between them have been designed by Elihu Thomson and by Stanley for the purpose of yielding alternating currents of a constant number of virtual amperes. Forms with much magnetic leakage answer this purpose. Swinburne[1] has pointed out that a hedgehog transformer will answer in this way if the primary and secondary coils are wound on opposite ends instead of being wound close together. An ordinary

[1] *Proc. Roy. Soc.*, February 1887.

transformer can be adapted to such service if a choking-coil is introduced into the primary circuit. The use of constant-current apparatus is for feeding arc and glow lamps in series.

Auto-Transformers.

The auto-transformer (or "one coil" transformer) merely consists of a coil of wire wound on an iron core, and connected across the mains. To some point in it, at a greater or less distance from one end, according to the voltage required, a branch wire is attached and current is drawn off between this branch and one end. In Fig. 505 the ends *p p* are attached to the primary mains, while *s s* act as the secondary terminals, giving out a lower voltage, and acting as a pressure-*reducer*. It will be seen that a greater current can be drawn off in this way than is actually supplied by the mains, as the portion of coil that is common to the circuits acts as the secondary of a transformer. Less copper is required than if there were two separate coils. If the connexions were made the other way, so that the lesser number of coils were connected to the mains, the voltage at the outer terminals would be raised; the arrangement then serving as an *augmentator* of pressure.

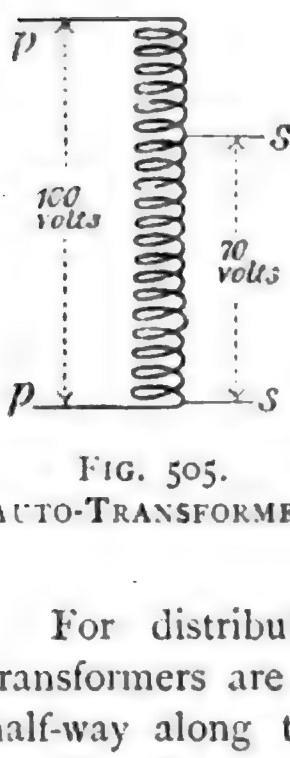


Fig. 505.
Auto-Transformer.

For distribution by the 3-wire system the secondaries of transformers are often wound to 200 volts, with a middle terminal half-way along the coil for the third wire of the network. For working three arc lamps in series at 33 volts each, from 100-volt mains, an auto-transformer is used having intermediate terminals, so that each lamp is a shunt to one-third of the coil.

Polyphase Transformers.

For the special forms of transformer used for 2-phase and 3-phase currents; and for transforming 2-phase to 3-phase currents, or *vice versâ*, the reader is referred to the author's treatise on *Polyphase Electric Currents.*

Theory of Alternate-current Transformers.

There are two ways of treating the theory of transformers. In the first, which lends itself the more easily to simple treatment, and has already been used on p. 699, the fundamental consideration is the alternating magnetic flux in the core, which induces electromotive-forces in the two windings, and is itself due to the resultant of the two sets of ampere-turns in the coils. This method has been elaborated by Hopkinson.[1] In the second the calculations are effected by introducing the notion of coefficients of mutual and self-induction into the differential equations for the two circuits. The latter method, due to Maxwell,[2] consists in finding the electromotive-force induced in the second circuit by the variations of current impressed upon the first circuit.

First let us consider the coefficients of mutual and self-induction. In order to calculate the mutual action of the two circuits we want to know the amount of cutting of magnetic lines by the *secondary* coils that takes place when unit current is made to flow, or is stopped in the *primary* coils. Let M be used as a symbol for this quantity. It will be proportional to the number of turns in the secondary coil, because each turn encircles the iron core and cuts the magnetic lines; it will also be proportional to the number of turns in the primary coil, because, *cæteris paribus*, the magnetism evoked in the iron core is proportional to the ampere-turns that excite it; it will also be proportional at every stage to the permeability of the iron core. We may, in fact, calculate M by the magnetic principles laid down in Chapter VI. Suppose the iron core to form a closed circuit of length l, section A, permeability μ; and that S_1 and S_2 are the respective numbers of turns in primary and secondary. Then, if the primary current is unity (in absolute C.G.S. units), the magnetomotive-force due to it will be $4\pi S_1$, and the reluctance will be $l / A\mu$. Dividing the former by the latter, we shall have an expression for the number of lines in the core; this multiplied by S_2 gives the amount of cutting of lines by the secondary circuit; or in symbols

$$M = 4\pi S_1 S_2 A \mu / l.$$

[1] *Proc. Roy. Soc.* February, 1887.

[2] *Philosophical Transactions*, clv. pt. i. p. 459, 1865. In this paper Maxwell shows that the effect of the second circuit is to add to the apparent resistance and diminish the apparent self-induction of the first circuit. The student will find the equations more fully treated by Mascart and Joubert, *Électricité et Magnétisme*, i. 593 and ii. 834; also by Hopkinson, *Journal Soc. Teleg. Engineers*, xiii. 511, 1884; Ferraris, *Mem. Acad. Sci.* (Turin), xxxvii. 1885; and by Vaschy, *Annales Télegraphiques*, 1885-6, or *Théorie des Machines Magneto et Dynamo-Electriques*, p. 31. A summary of Maxwell's work is given in Fleming's book.

The name given to this quantity is the *coefficient of mutual induction.* If the current in the primary have the value C_1 (absolute C.G.S. units), then the amount of cutting by the secondary on turning this current on or off will be $M\,C_1$. And if the rate of increase or decrease of the primary current at any instant is known, this multiplied by M will give the electromotive-force impressed at that instant on the secondary circuit.

Considerations precisely analogous to those above will show that there will be a *coefficient of self-induction,* which we will call L_1, which represents the amount of cutting, by the primary coil, of the magnetic lines created in the coil when the primary coil carries unit current; and, as before, the value of this coefficient will be

$$L_1 = 4\,\pi\,S_1^2\,A\,\mu\,/\,l.$$

As S_1 is itself usually large, L_1 will be enormous. Further, there will be a coefficient of self-induction L_2 in the secondary circuit, such that

$$L_2 = 4\,\pi\,S_2^2\,A\,\mu\,/\,l.$$

In a well-built transformer it is clear that

$$M = \sqrt{L_1\,L_2}.$$

If, however, all the magnetic lines due to one circuit are not enclosed by the other, M will have a less value than is indicated by the above relation. (See a recent paper by Dr. Bedell read at the Chicago Congress, 1893.)

The ratio between the two electromotive-forces and the two sets of windings,

$$\frac{S_1}{S_2} = k,$$

we call the *coefficient of transformation.*

If it is assumed that there are equal weights of copper used in the primary and secondary coils, then the following relations will hold good :—

	Primary.	Secondary.	Ratio.
Windings	S_1	S_2	k
Resistance	r_1	r_2	k^2
Self-induction	L_1	L_2	k^2
Electromotive-force	E_1	E_2	k
Current	C_1	C_2	k^{-1}
Heat-waste	$C_1^2\,r_1$	$C_2^2\,r_2$	1

Also
$$M = \frac{L_1}{k} = k L_2.$$

Maxwell's Theory.—At any given instant the impressed electromotive-force in the primary circuit must be sufficient not only to drive the current C_1 through the resistance R_1 of that circuit, but must also be adequate to counterbalance the reactions arising from mutual and self-induction. These at that instant will have the respective values $M \frac{dC_2}{dt}$ and $L \frac{dC_1}{dt}$.

Accordingly we write as the differential equation of the first circuit—

$$E_1 - M \frac{dC_2}{dt} - L_1 \frac{dC_1}{dt} - R_1 C_1 = 0; \tag{1}$$

where E_1 is the impressed electromotive-force of the generator which is supposed to fulfil the condition $E_1 = D \sin 2 \pi n t$ (see p. 549). If the supposition is admitted that a constant (alternating) potential can be maintained at the terminals of the primary coil (by proper compounding of the alternator, or otherwise), then the letters E, L , and R_1, may be taken to apply to that part of the primary circuit only which lies between the terminals of the primary coil. From this differential equation we have to deduce a value for $M \frac{dC_2}{dt}$. For brevity we will write p for $2 \pi n$; and $-p^2 C$ for $\frac{d^2 C}{dt^2}$, because C is also assumed to be a sine-function. Then differentiating equation (1) we get—

$$\frac{dE_1}{dt} + M p^2 C_2 + L_1 p^2 C_1 - R_1 \frac{dC_1}{dt} = 0. \tag{2}$$

Now multiply this by R_1 to get equation (3), and multiply equation (1) by $L_1 p^2$ to get equation (4); and add (3) and (4) to get (5).

$$R_1 \frac{dE_1}{dt} + M p^2 R_1 C_2 + L_1 p^2 R_1 C_1 - R_1^2 \frac{dC_1}{dt} = 0. \tag{3}$$

$$L_1 p^2 E_1 - L_1 p^2 M \frac{dC_2}{dt} - L_1^2 p^2 \frac{dC_1}{dt} - L^1 p^2 R_1 C_1 = 0. \tag{4}$$

$$\left(R_1^2 + L_1^2 p^2\right) \frac{dC_1}{dt} = R_1 \frac{dE_1}{dt} + L_1 p^2 E_1 + M p^2 \left(R_1 C_2 - L_1 \frac{dC_2}{dt}\right). \tag{5}$$

Now multiply every term by $\frac{M}{R_1^2 + L_1^2 p^2}$, and write the following abbreviations:—

$$\frac{M p}{\sqrt{R_1^2 + L_1^2 p^2}} = \frac{1}{k}$$

$$R_1 / k^2 = \rho,$$

$$L_1 / k^2 = \lambda,$$

Then

$$-\frac{1}{k M}\left(\frac{R_1}{p} \cdot \frac{dE_1}{d t} + L_1 E_1\right) = E_2 = \frac{1}{k} E_1 \sin (p t - \phi),$$

where ϕ relates to the phase of the electromotive-force; and we may write equation (5) as—

$$M \frac{d C_1}{d t} = \rho C_2 - \lambda \frac{d C_2}{d t} - E_2. \tag{6}$$

Now the differential equation for the second circuit is—

$$M \frac{d C_1}{d t} + L_2 \frac{d C_2}{d t} + R_2 C_2 = 0; \tag{7}$$

there being in this circuit no other electromotive-forces than those due to mutual and self-induction. Inserting in (7) the value obtained in (6), we get as the final equation—

$$(R_2 + \rho) C_2 + (L_2 - \lambda) \frac{d C_2}{d t} - E_2 = 0. \tag{8}$$

Examination of the quantity k shows us that if R_1 be small enough or p large enough, it becomes equal to $\frac{L_1^2}{M}$; or is the same thing as the ratio of the windings for which we have used the same symbol. Then returning to interpret equation (8) we see that it shows us that the whole effect is equivalent to that which would happen if, the primary circuit being absent, there were introduced into the secondary circuit an electromotive-force equal to E_1 divided by k, and at the same time the resistance were increased by a quantity equal to R_1/k^2, and the self-induction were diminished by a quantity equal to L_1/k^2. If there are equal weights of copper in the two windings $L_2 = L_1/k^2$, and $R_2 = R_1/k^2$; and the effect when the

transformer is fully at work is to make ρ equal to the internal resistance of the secondary, and λ equal to L_2, so that the internal resistance is virtually doubled and the self-induction wiped out.

Professor Perry has contributed several important papers[1] on the theory of transformers, in which he has treated leakage and multiple secondaries mathematically.

[1] *Phil. Mag.*, August 1891 ; and *Proc. Roy. Soc.* li. p. 455, May 1892.

CHAPTER XXVII.

MOTOR-GENERATORS.

MOTOR-GENERATORS are revolving transformers for effecting transformations which cannot be effected by stationary apparatus. They are of two sorts: (1) for transforming a continuous current at any voltage into a continuous current at any other voltage; (2) for transforming continuous currents into alternating currents (single-phase or polyphase) or *vice versâ*. In every case the apparatus consists essentially of a combination of a motor with a generator.

CONTINUOUS-CURRENT TRANSFORMERS.

Gramme, in 1874, constructed a machine with a ring-armature wound with two circuits—one of coarse wire, the other with fine wire, having eight times as many turns. Two separate commutators were connected with the two windings. This machine could be used for transforming either from high to low potential or *vice versâ*. The same end can be less conveniently attained by uniting on one shaft the armatures of two dynamos, one to be used as a motor driving, the other as a generator; and these may have separate field-magnets or a common field-magnet. There is very little sparking with such machines, as the reactions in the two sets of coils tend to correct each other. The field-magnet is usually excited as a shunt to the low-potential armature coil. Swinburne has discussed many possible combinations, including one for transforming from a constant-current to a constant-potential condition of distribution. The chief use hitherto for continuous-current transformers has been for transmission of current at high voltage, so as to economise copper in the feeding mains. In England, continuous-current transformers have been introduced with success by various firms. Messrs. Laurence, Paris and Scott[1] employ a 2-pole machine with

[1] See *Electrician*, xix. 517, October 1887; and *Electrical Review*, xxii. 4, 1888.

cast-iron frame and an armature wound with double circuits. In the Chelsea central station a number of motor-dynamos are used. They have been described in detail by Major-General Webber,[1] and include several types, some being by Laurence and Scott, others of Elwell-Parker construction. In the city of Oxford continuous currents generated at 1000 volts are transmitted to motor dynamos at several points of the city where they feed the network at 100 volts.

The following are particulars of an Elwell-Parker bipolar continuous-current transformer, with drum-wound armature but having a commutator at each end.

	Primary.	Secondary.
Volts	1000	110
Amperes	40	360
Resistance of armature winding (ohms)	0·427	0·0052
Conductors around armature ..	648	72
Segments in commutator	162	36

Speed 500 revolutions per minute.
Field-magnets: shunt-wound with 3080 turns; resistance 8·5 ohms.
Armature core: diameter of disks $16\frac{5}{16}$ in.; nett cross section of iron 326 sq. in.
Efficiency of double transformation: at full load 83 per cent.; at half load 75 per cent.

Fig. 506 shows a small continuous-current transformer constructed by the Crocker-Wheeler Co. for the author, for testing purposes. It transforms a current of 10 amperes at 100 volts to one of 1 ampere at 1000 volts. Mr. T. Parker winds motor-dynamos with Eickemeyer coils, the high-pressure windings being completed and connected up first. Then the whole surface is insulated afresh, and the low-pressure windings are laid on in outer layers.

A second use for continuous-current transformers is the production of large currents at very low voltage, as for electrotyping and for meter testing.[2]

A third service for which motor-dynamos are employed is to compensate the drop in voltage on long mains by inserting into the main at a distant point a series motor driving an armature placed as a shunt across the mains. Lahmeyer[3] calls this device a

[1] *Journal Inst. Electrical Engineers*, xx. 63 to 69, 1891, giving drawings and data of three machines.
[2] See *The Engineer*, Aug. 11, 1893.
[3] *Centralblatt für Elektrotechnik*, xi. 402, 1889.

"far-leading" dynamo (Fernleitungs-dynamo). American electricians term it a "booster." Sayers has described such machines fitted with his compensating winding (p. 395). (See *Electrician*, xxxi. 677).

A fourth application is for charging accumulators at a higher voltage than that of the generator, so that lamps may be run either direct or from the cells.

A fifth use is for 3-wire and 5-wire systems of distribution, a number of armatures or windings on the same shaft being connected across the various pairs of mains. If at any pair of mains the potential drops, this armature will begin to feed this pair, being driven by the other armatures as motors. Such a device is called an "equalizing" dynamo (Ausgleichungs-dynamo).

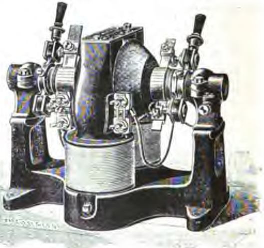


FIG. 506.—CONTINUOUS-CURRENT TRANSFORMER (Crocker-Wheeler Co.).

The following are particulars of transformers or "equalizers," as they may be properly called, recently constructed by Messrs. Mather and Platt for the 5-wire supply in Manchester. The machines have drum-armatures with the bar winding described on p. 306, with shunt-wound magnets of "Edison-Hopkinson" type.

Resistance of magnets	25 ohms.
Resistance of each armature winding	·0126 ohm.

With an output on one side of 126 amperes at 103·4 volts, the output

on the generator side was 112 amperes at 100·4 volts. Hence the efficiency of double conversion, including all frictional and mechanical as well as electrical losses, is 83·5 per cent.; or looked at from the point of view of the purpose for which the machines are specially intended, if there is a difference of 3·0 volts between the two sides of a 3-wire system, they will transfer 112 amperes from the higher to the lower side. The journals of these machines run on ball bearings.

A somewhat different system of continuous-current transformation has been suggested by Cabanellas,[1] and patented by Edison,[2] in which neither armature nor field-magnet revolves, but in which, by means of a revolving commutator, the magnetic polarity of a double-wound armature is continually caused to rotate. In a further modification of this idea, due to Jehl and Rupp, a mass of iron, which completes the magnetic circuit, rotates within the double-wound ring.[3]

Spark troubles, however, afflict all merely commutating machines.

For further notices of the methods of continuous-current transformation, the reader is referred to articles by Elihu Thomson, in *Electrical World*, x. 108, 1887; by R. P. Sellon, in *Electrician*, xx. 633, 1888; and by Rechniewski, in *La Lumière Électrique*, xxv. 416, 1887; and see *Electrician*, xxxi. 677.

Theory of Continuous-current Transformers.

Let $\mathcal{E}$ be the potential at terminals of the primary or motor part, and e that at terminals of the secondary or generator part. Let the C_1, r_1, and Z_1 stand respectively for the armature current, armature resistance, and number of armature conductors of the primary part; and C_2, r_2, and Z_2 for the corresponding quantities of the secondary part. Then the two induced electromotive-forces will be—

$$E_1 = n Z_1 \mathsf{N}, \text{ and } E_2 = n Z_2 \mathsf{N}; \text{ and}$$
$$E_1 = \mathcal{E} - r_1 C_1, \text{ and } E_2 = e + r_2 C_2.$$

Now write k for $Z_1 \div Z_2$ (the *coefficient of transformation*), and we have—

$$k e = \mathcal{E} - r_1 C_1 - k r_2 C_2.$$

[1] See *La Nature*, p. 43, 1882.

[2] Specification of Patent, 3949 of 1882; and *Electrician*, xix. 479, 1887.

[3] See *Electrician*, xix. 514, 1887; xx. 7, 1887; and Specification of Patent, 2130 of 1887.

But the electric work done on and by the armature is equal, assuming loss by eddy-currents and hysteresis to be negligible, or $E_1 C_1 = E_2 C_2$; whence $C_2 = k\,C_1$, so that the last equation becomes—

$$e = \frac{\mathcal{E}}{k} - \left(r_2 + \frac{r_1}{k^2}\right)C_2.$$

This shows that everything goes on in the secondary circuit as though the potential were reduced from that of the primary mains in proportion to the respective numbers of windings on the armature; and as though there were added to the internal resistance of the secondary circuit a resistance equal to that of the primary winding divided by the square of the coefficient of transformation. The ratio of transformation is independent of the speed and of the magnetism, though these two quantities depend inversely on one another. If the dynamo (or secondary) part is compound wound the speed may be very nearly constant at all loads; but there is little advantage in this, as the speed always adjusts itself to what is wanted. If the distant generator supplying the system is properly over-compounded it will keep the voltage at the lamps constant, though the transformer is interposed. The objections to the use as transformers of running machines are almost entirely met by the considerations that these machines run sparklessly (owing to the balancing of the self-inductions of the two windings), and with very little friction at the bearings, because the driving and driven parts are both contained in the one rotating part. The brushes once set need not be moved at any load.

Continuous-alternating Transformers.

To change an alternating current to a continuous one, or *vice versâ*, there is required a combination of an alternator and a continuous-current machine, serving one as generator, the other as motor. This may consist of two separate machines coupled together, as shown in Fig. 508, which represents an alternator combined with an internal-pole continuous-current dynamo, both of Siemens' pattern, to transform from 2000 volts alternating to 150 volts continuous, for charging accumulators, &c. The town of Cassel is supplied with continuous currents transmitted as alternate currents at high voltage and transformed down by a Kapp alternator (as motor) driving two dynamos. At Buda-Pesth the trans-

mission is 2-phase, with coupled plant at sub-stations to give out continuous currents.

But it is not necessary for this purpose to couple two separate machines. A single winding revolving in a bipolar field, Fig. 507, joined up not only to two slip-rings, but also to a commutator, will work either as motor or generator for either alternating or continuous currents, and therefore can give out either kind when driven by the other.[1] In practice, a more complex armature with a many-part commutator is used. For example, an ordinary Gramme ring is used with the addition of two slip-rings which are conducted to two points

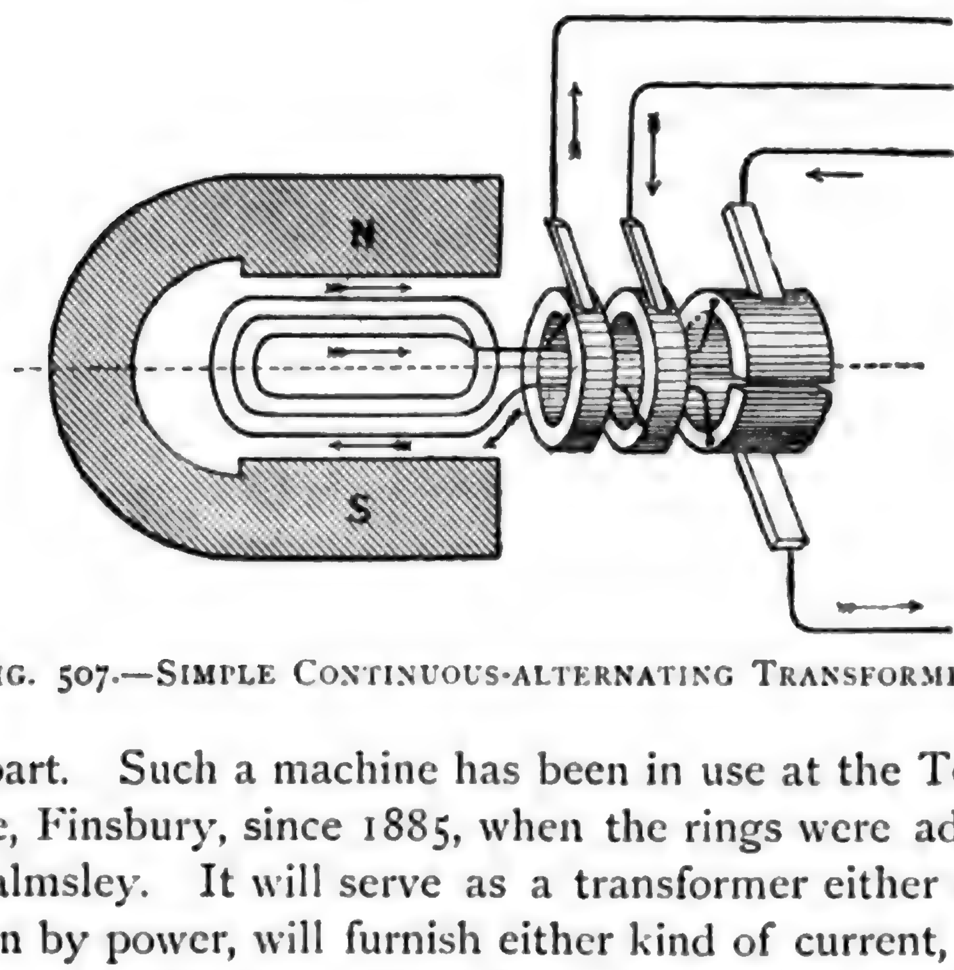


FIG. 507.—SIMPLE CONTINUOUS-ALTERNATING TRANSFORMER.

180° apart. Such a machine has been in use at the Technical College, Finsbury, since 1885, when the rings were added by Dr. Walmsley. It will serve as a transformer either way, or, if driven by power, will furnish either kind of current, or both at once. In 1887, the Helios Co., and in 1889, Mr. Bradley and Mr. Tesla patented similar devices. For producing 3-phase currents from continuous currents, three slip-rings must be connected on at three symmetrical points. For 2-phase currents four slip-rings are connected at points 90° apart. In a recent apparatus of Hutin and Leblanc[2] there is

[1] M. Hospitalier proposes to call machines of this class *polymorphic* dynamos. See *Soc. Française de Physique*, 1894, p. 204.

[2] See an illustrated article in *L'Électricien* of April 21, 1894.

employed a row of eighteen slip-rings connected at as many symmetrical points, and giving rise to eighteen alternate currents, each differing in phase by 20° from its next neighbour.

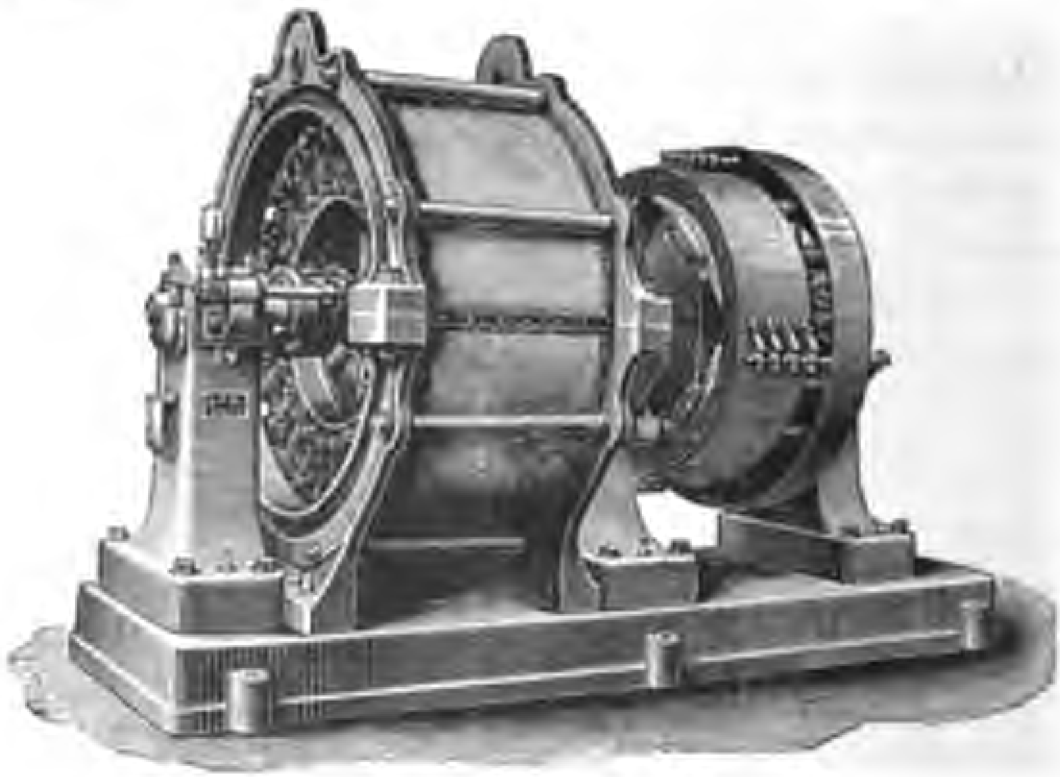


FIG. 508.—CONTINUOUS-ALTERNATING TRANSFORMER.

A simple revolving combined commutator like that of Fig. 509, would, without any field-magnet, suffice to convert continuous into alternating currents, or to rectify alternate

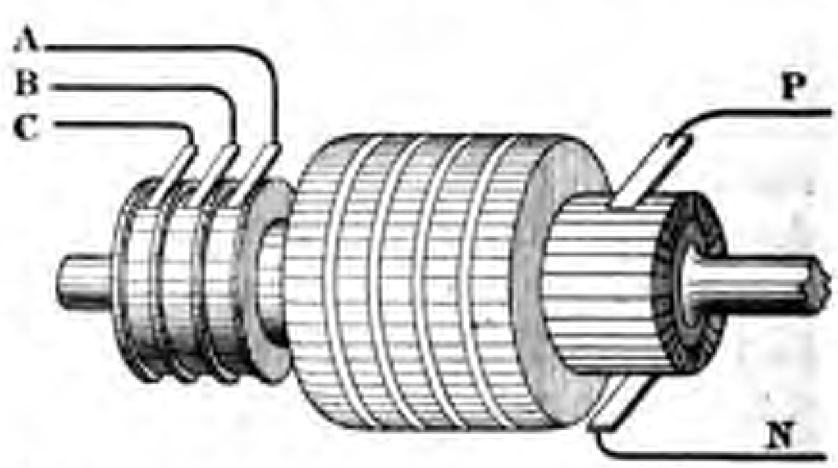


FIG. 509.—TRANSFORMER ARMATURE FOR 3-PHASE AND CONTINUOUS CURRENT.

currents into continuous, were it not for the practical difficulties arising about sparking. The use of the field-magnet is to balance the electromotive-forces in the different parts of the windings, as well as to maintain the proper rotation.

Pollak, of Frankfort, and Ferranti have both successfully used rectifying commutators, the former for charging accumulators, the latter for arc lighting.

At the Frankfort Exhibition of 1891 many revolving transformers were shown. The firms of Lahmeyer and Schuckert, in particular, displayed many very interesting forms of polyphase apparatus, in which this feature was prominent.

Messrs Schuckert and Co. showed a 6-pole ring-wound machine, capable of transforming from a continuous current or single-phase, 2-phase, or 3-phase currents to currents of any or all of the other three kinds. It consists of an ordinary ring armature with a 144-part commutator, whose windings in front of the different pairs of poles are cross-connected in parallel (Mordey's well-known method). As there are 144 sections in the winding, and six poles, the number of sections that lie between any pole and the next pole of the same sign will be 48. From Nos. 1, 17 and 33, that is to say, at points equally spaced out at distances of one-third of the extent of the winding between any pole and the next pole of the same sign, are attached three wires which are brought down to three slip-rings from which brushes supply 3-phase currents. To four points also equally spaced along the same section of the winding (namely, Nos. 1, 13, 25 and 37), are attached four wires, which going to four other slip-rings, supply both single and 2-phase currents.

An 8-pole revolving transformer on a similar principle, but having a wave-wound drum armature, was shown at Frankfort by the Allgemeine Company. It could receive continuous current at about 100 volts, and transform this into 3-phase currents at about 70 volts. This transformer is now in the laboratory of the Technical College, Finsbury.

The most important motor-dynamos yet made are those constructed at Schenectady for the Niagara works.[1]

They are 20-pole multipolar drum machines, having the ordinary commutator, but also having four slip-rings added, at the back of the armature. They receive the 2-phase current already transformed down to 115 volts and deliver 3000 amperes at 150 volts for the purpose of aluminium reduction.

[1] See *Cassier's Magazine*, 1895, p. 334.

CHAPTER XXVIII.

ELECTRIC TRANSMISSION OF ENERGY.

IN all problems relating to the electric transmission of power, whether over short or long distances, it is vital to remember that the two factors to be considered are the *current* and the *pressure* (or voltage) at which it is transmitted. In the ordinary distribution of electric energy from central stations in cities, whether with direct or alternating currents, it is usual to observe the condition of *constant pressure*, the current being varied in proportion to the demand. But for series lighting, it is possible to observe the other condition of maintaining a *constant current*, the pressure being varied in proportion to the number of lamps in the circuit. It is well to bear this distinction in mind in the problem of transmission to a distance, although in fact power may be electrically supplied without conforming to either of these prescribed conditions of supply. We have seen, p. 492, how it came to be recognized that the secret of success in long-distance transmission lay in the use of high voltages, as this permitted the use of small currents, and therefore of thin conducting wires. We may with advantage recapitulate the problem of economy of transmission.

It is required first to determine the relation between the pressure at which the current is supplied to the motor, and the heat-waste in the circuit.

Let Σ R stand for the sum of all the resistances in the circuit; then, by Joule's law, the heat-waste is (in watts) $C^2 \Sigma R$. And since $C = \frac{\mathcal{E} - E}{\Sigma R}$, we may write:

$$\text{heat-waste} = \frac{(\mathcal{E} - E)^2}{\Sigma R}.$$

Now suppose that without changing the resistances of the circuit we can increase $\mathcal{E}$ to $\mathcal{E}'$, and also increase E to E', while keeping $\mathcal{E}' - E'$ the same as $\mathcal{E} - E$, so that the current will be the same: it is clear that the heat loss will be precisely the same as before, while more energy is transmitted. The efficiency is greater, for

$$\frac{\text{power of motor}}{\text{power of generator}} = \frac{C E'}{C \mathcal{E}'} = \frac{E'}{\mathcal{E}'},$$

and this ratio is more nearly equal to unity than $\frac{E}{\mathcal{E}}$, because both $\mathcal{E}$ and E have received an increment arithmetically equal. As an example, suppose $\mathcal{E}$ to be 100 volts and E 90 volts, and the sum of the resistances to be 1 ohm. Then C will be 10 amperes. The power supplied will be 1000 watts; that utilised will be 900 watts; the heat-waste is 100 watts; and the electrical efficiency 90 per cent. Now suppose the voltages increased so that $\mathcal{E}'$ is 1000 volts, and E' 990 volts. The current will still be 10 amperes. The power supplied will be 10,000 watts, of which 9900 will be utilised and 100 wasted in heat. We have 10 times as much power transmitted, with the same heat-waste as before, and the efficiency has risen to 99 per cent. Clearly, then, it is an economy to work at high voltage.

High voltage can be attained in several ways: by winding armatures with many turns of fine wire, by using higher speeds and by putting several machines in series. In the case of alternate currents there is the additional resource of using step-up transformers (see p. 738 and p. 741).

The advantage derived in the case of the electric transmission of energy from the employment of very high electromotive-forces in the two machines is also deducible from the diagram.

Let Fig. 328, given on p. 499, be taken as representing the case where $\mathcal{E}$ is 100 volts and E 80 volts. Now suppose the resistances of the circuit to remain the same while $\mathcal{E}$ is increased to 200 volts and E to 180 volts. $\mathcal{E} - E$ is still

20 volts, and the current will be the same as before. Fig. 510 represents this state of things. The square K G H D which represents the heat-waste is the same size as before; but the energy spent per second is twice as great, and the useful work done is more than twice as great as previously.

We may look at the matter from a different point of view. Power being made up of the two factors E and C, if it is required to transmit a certain prescribed number of watts we will by preference make E high and C low, for it is the flow of the current through the resistances of the circuit that causes the loss, while the only disadvantage of a high electromotive-force is the difficulty in preserving the insulation. The electromotive-force will therefore be made as high as it can be made consistently with safety. If we double the pressure, thereby reducing the current to one-half, we reduce the loss to one-quarter, as the loss is proportional to the square of the current.

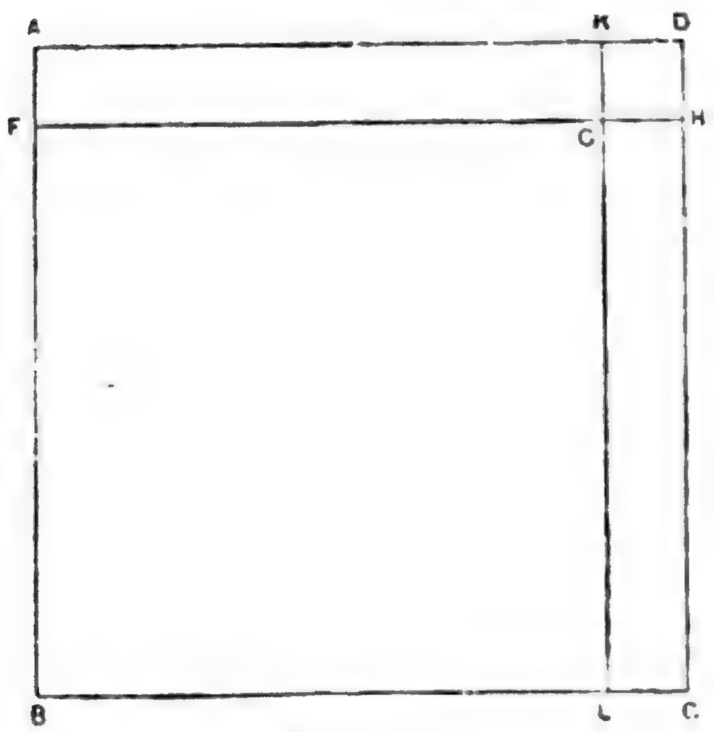


FIG. 510.

In an experiment, M. Fontaine,[1] by using several Gramme machines coupled in series at each end of a line, the resistance of which was 100 ohms, succeeded in transmitting 50 horse-power with a mechanical efficiency of 52 per cent. This experiment realised the suggestion made in 1879 by Elihu Thomson for the economic use of several machines in series. Seven machines were used, of similar construction, of the "over" type, each weighing 1200 kilogrammes, and of about 16 kilowatts capacity. Four were united in series at the generating end, and driven at 1298 revolutions per minute by a

[1] *L'Electricien*, x. 707, 1886.

steam engine indicating 113 H.P. Brake tests at the generating end showed the actual H.P. to be 95·88. The other three machines were used as motors, their power being measured by a brake. They gave out 49·98 H.P. at 1120 revolutions per minute. The current was 9·34 amperes. The result is that there was a nett efficiency of 52 per cent. The resistance of the machines was about 11½ ohms each. The voltage at the generating end of the line was 5996 volts; that at the receiving end was 5062 volts.

Efficiency of Transmission.—It can readily be shown that with two series dynamos, the electrical efficiency of transmission, when there is no leakage, is the ratio of the electromotive-forces developed in the armatures of the two machines. To do this we will consider separately the efficiencies of the three parts of the system. Writing E_1 for the electromotive-force developed in the generator, E_2 for that of the motor, r_1 and r_2 for their respective internal resistances, we shall then have

$$\text{Efficiency of generator} \quad .. \quad \eta_1 = \frac{E_1C - r_1 C^2}{E_1 C};$$

$$\text{Efficiency of line} \quad .. \quad .. \quad \eta_2 = \frac{E_2C + r_2C^2}{E_1C - r_1C^2};$$

$$\text{Efficiency of motor} \quad .. \quad .. \quad \eta_3 = \frac{E_2C}{E_2C + r_2C^2}.$$

Hence the resulting efficiency of the whole system will be

$$\eta = \eta_1 \times \eta_2 \times \eta_3 = \frac{E_2}{E_1}.$$

If the machines are shunt-wound or compound-wound, or if there is leakage on the line, the currents through the armatures will no longer be alike in the two machines. Writing the respective armature currents as i_1 and i_2, we shall have in this case, as the electrical efficiency of transmission,

$$\eta = \frac{E_2 C_2}{E_1 C_1}.$$

As an example of transmission to a moderate distance by continuous currents we may cite the plant at Schaffhausen erected by the Oerlikon Works of Zürich where 500 actual horse-power are delivered to the spinning mills electrically, with a nett efficiency of 78 per cent. from turbines in the river 750 yards away, two generators (6-pole over-compounded dynamos designed by C. E. L. Brown) being used to give each 330 amperes at 624 volts. The motors, which are of the same type, are constructed with field-magnets which are relatively more powerful than those of the generators, and run without varying more than 3 per cent. in speed between no-load and full load. The commutators are guaranteed to last for 20,000 hours.

Another example[1] of transmission with continuous currents is afforded by the plant for supplying power to mills and to a central lighting station at Genoa. Water power derived from a tributary of the Po is converted for transmission in several stations on the mountain side at a distance of 16 miles from Genoa. In one of these stations there are eight Thury continuous-current machines of 70 H.P. each, coupled in pairs to 140 H.P. turbines. Each machine yields 47 amperes at 1000 volts. They are separately insulated on porcelain and coupled in series so that the power is transmitted at a total pressure of 8000 volts. The conductor is of bare copper carried on oil insulators.

When a very high electromotive-force is required for the purpose of transmitting power, it is found convenient to use alternating currents (p. 547) for the two following main reasons.

(1) Alternate-current generators require no commutator, and therefore the current can be generated by one machine at the full pressure required.

(2) Alternate currents can be transformed from one pressure to another by means of a simple transformer without moving parts.

The objections to alternate currents for this purpose are:—

(1) As the maximum pressure with alternate currents is 1·41 times the $\sqrt{\text{mean}^2}$ pressure, an alternate current of a certain value will not transmit as much power along a line as

[1] *Elek. Zeitsch.* 1892, xiii. 216; *Journ. Inst. Elec. Eng.*, 1892, xxi. 534.

a continuous current of equivalent value whose pressure is equal to the maximum pressure of the alternate current.

(2) There may be a loss of *power* in the line due to the wattless current (p. 567).

(3) There is a certain amount of loss of *pressure* in the line due to self-induction apart from the resistance of the line (p. 559).

(4) There is a slight increase in the resistance of the mains due to skin effect if the frequency is high or the currents large (p. 578).

(5) Until recently alternate currents for transmitting power were open to the objection that alternate-current motors were not self-starting. This objection is removed by the introduction of self-starting monophase motors of high efficiency (p. 687), and by the employment of polyphase currents (p. 662).

The two advantages of alternate currents mentioned above so much outweigh the objections, that in the majority of cases of long-distance transmission in all parts of the world alternate currents are used.

In the largest scheme for the distribution of power ever undertaken, namely, from the Niagara Falls, alternate currents in two phases are used. The 5000 H.P. dynamos for generating the current are described on p. 638. They are three in number and yield 1550 amperes each (775 amperes in each circuit) at 2250 volts. The power is intended for distribution to factories in the immediate vicinity, and also for transmission to considerable distances. Continuous currents for aluminium smelting are obtained by means of rotating transformers. For distribution to great distances the pressure is raised by transformers to 20,000 volts. The water power available is about 100,000 H.P., and this will be utilized from time to time as the demand increases. It is probable that some of the future dynamos will generate the current for distant transmission at the full pressure without the intervention of step-up transformers. A subway carries the main conductors for a distance of 2500 feet, the conductors consisting of bare copper strip carried on oil insulators. From this subway branches are taken to neighbouring factories.

An instance of transmission of power at high pressure which has been in existence for over three years is at Hochfelden, Switzerland, carried out by the Oerlikon Co. Fig. 511 gives a view of the station showing the three generators, which were designed by Mr. C. E. L. Brown, in 1890. They are 3-phase machines, each of 200 horse-power, running at 180 revolutions per minute. Excepting in having the vertical shafts directly above the turbines by which they are driven, they closely resemble the Lauffen generators. They give 86 volts pressure between the terminals. To raise the voltage each is connected to a 3-phase transformer immersed in oil, one of these transformers being visible on the right hand of the cut. The pressure is raised to 13,000 volts, at which pressure the currents are conveyed by three wires, each 4 mm. in diameter, to the Oerlikon Works (a distance of 24 kilometres, or about 15½ miles), where by means of step-down transformers of similar construction the pressure is lowered to 190 volts, and the currents are distributed for lighting and power at this pressure.

Graphic Representation of Transmission.—A convenient mode of representing graphically the relative amounts of energy expended at the transmitting end and utilised at the receiving end is the following, which is due to von Hefner Alteneck:—

Let (Fig. 512) the perpendicular lines $A E_1$ and $B E_2$ represent respectively the electromotive-forces at the transmitting and receiving machines; and let the horizontal lengths $A L_1$, $L_1 L_2$, and $L_2 B$ represent respectively the resistances of the machine at A, the line (including return wire), and of the machine at B. Join $E_1 E_2$: the tangent of slope $(E_1 F \div F E_2)$ of this line will represent the current flowing. From A and from B drop perpendiculars upon this sloping line, and produce them to the points W_1 and W_2, level with E_1 and E_2. The length of the lines $E_1 W_1$ and $E_2 W_2$ will represent relatively the energy transmitted and received. For, by the construction each is proportional to the respective electromotive-force and to the slope of $E_1 E_2$. The energy lost in heat may, on the same scale, be represented by the length of the line $E_1 H$.[1]

[1] For a further geometrical discussion of the problem of electric transmission of power, see a paper by Reignier, in *La Lumière Électrique*, xxiii. 352, 1887.

FIG. 511.—THREE-PHASE GENERATORS AT THE POWER STATION AT HOCHFELDEN (SWITZERLAND).

Economy of Transmission.—As already shown, the economy of transmission depends on the voltage at which the power is transmitted, and on the resistance of the line. The question then arises at what amount ought the latter to be fixed to make the economy a maximum. If one saves heat-waste by putting up a thick copper wire for the line, the interest on the prime cost of the line may more than balance the saving in power. An answer was given in 1881, by Lord Kelvin, to one form of the problem, in which it is assumed (1) that the voltage is fixed, (2) that the power to be transmitted is a fixed amount. If these are the conditions, then the total annual cost of the power wasted in the resistance of the line and of the interest on the copper

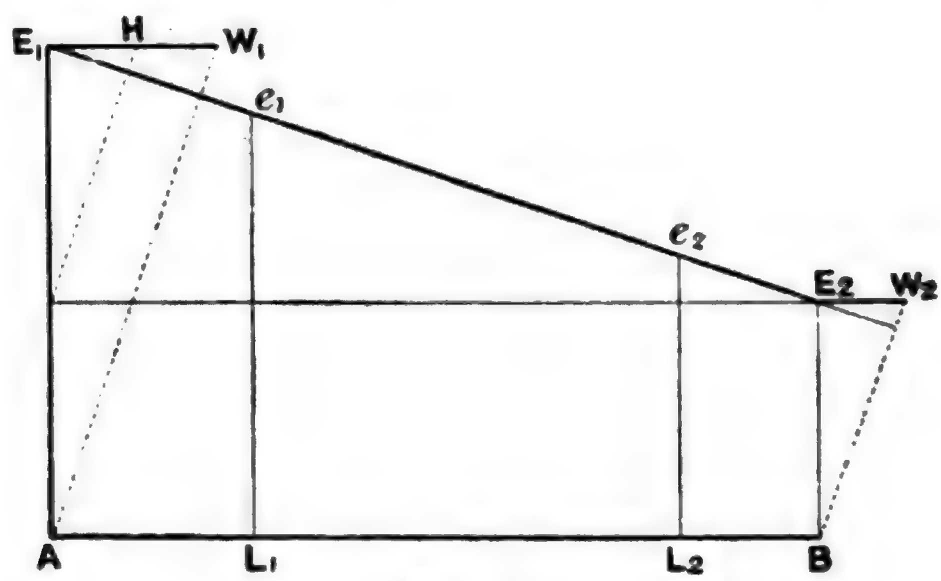


FIG. 512.

(including insulation and erection) will be a minimum when these two annual items of cost are equal to one another. Much confusion has arisen from the ignorant application of Thomson's law to other cases than those for which it is true. In 1886, Professors Ayrton and Perry[1] considered some other cases, and have arrived at several important conclusions. If a given amount of power has to be furnished by a motor at one end of a line, using a given voltage at the generator at the other end, maximum economy is obtained, not by keeping the current-density constant, but by making it less, as the length of line to be used is greater. The smaller the voltage that may be employed at the generator, the smaller must the current-density in the line be to obtain the maximum efficiency. More recently, Mr. Kapp,[2] in his Cantor Lectures, has given a more

[1] *Journal Soc. Telegr. Engineers*, xv. 120, 1886.

[2] *Journal Soc. Arts*, xxxix., July 10, 1891; also his book on *Electric Transmission of Energy*, 4th edition, 1894, in which some very useful curves are given.

general solution, taking into account the voltage and the cost of the machines as well as that of the line. It is assumed that the annual value of power at the generating station is known, as well as the cost of plant per horse-power. Of the data required to be known, such as primary horse-power, total efficiency, voltage at motor, annual cost of power delivered, and working current, the last-mentioned is the most important to be calculated, for from it the other matters can then be found. Kapp finds that under no circumstances will it be economical to lose more than half the power in the line.

A useful set of tables, showing the cost of laying one additional ton of copper, meaning thereby that part of the capital outlay which is proportional to current, was given by Prof. G. Forbes in his Cantor Lectures [1] of 1885 on the Distribution of Electricity.

The secret of economy in all long-distance transmission lies, as we have seen, in the use of high voltage. But it is found in practice that continuous-current machines cannot advantageously be used at such high voltages as 3000 and 4000 volts, inasmuch as the commutators will not stand the strain on their insulation. Even putting several machines in series, though it lessens the voltage on each dynamo, does not prevent the risk of break-down of insulation. Hence the superiority of alternate-current apparatus, which requires no commutator. Moreover, where voltages exceeding 10,000 volts are desired, it is found preferable to use low-voltage alternators and motors, and to insert step-up transformers at the generating end, and step-down transformers at the receiving end (as proposed in 1881 by Deprez and Carpentier), since it is much easier to insulate thoroughly the stationary windings of a transformer than the parts of any running machinery. The question whether, of alternating systems, the ordinary single-phase, or one of the more novel 2- or 3-phase systems, is to be preferred in long-distance transmission is still an undecided matter.

As an example of long-distance transmission at an extra-high voltage may be cited the experimental line erected in the summer of 1891, from Lauffen to Frankfort, a distance of 175 kilometres. At Lauffen a special low-pressure turbine was fixed in the river Neckar to drive the 3-phase alternator, by Brown, described on p. 627, capable of giving (at full power) three alternating currents of about 1400 amperes each at 50 volts. These currents were converted by special transformers into three smaller currents at 8000, 12,500 or 25,000 volts. Three copper wires, each 4 mm. in diameter

[1] *Journal Soc. Arts*, 1885.

were carried to Frankfort on tall poles; about 10,000 porcelain insulators being employed, with oil-cups for high insulation. At Frankfort the currents were received into step-down transformers and reconverted to the low pressure of about 60 volts, to supply either lamps or 3-phase motors. Tests were made by a jury, having Prof. H. F. Weber as its head. Their report concludes with the following summary:—

(1) In the Lauffen-Frankfort plant for the electric transmission of energy over a distance of 170 kilometres, by means of a system of alternating currents, with a pressure of 8500 to 7500 volts, and bare copper conductors insulated by oil and porcelain, the lowest output in the tertiary circuit at Frankfort was 68·5 per cent., and the highest output was 75·2 per cent. of the energy given out by the turbine at Lauffen.

(2) In this transmission to a distance, the only cause of loss measurable by the instruments was that due to the resistance of the circuit (Joule's effect).

(3) Theoretical considerations showed that the influence of capacity upon long aerial bare conductors for transmission of energy to a distance by alternate currents, under the conditions employed, and with use of a frequency of 30 to 40 periods per second, is of so entirely subordinate a magnitude, that it need not be considered in designing electric transmissions.

(4) As the expression of our experience during the foregoing measurements for the determination of the efficiency of the Lauffen-Frankfort transmission of energy, we add, as a fourth result:—The electrical running with alternate currents of 7500 to 8500 volts in conductors of more than a hundred miles in length, insulated by means of oil, porcelain, and air, proceeds just as regularly, safely, and as free from disturbances as does running with alternate currents of a few hundred volts pressure over conducting wires of a few metres length.

In some further researches,[1] with a high pressure of 25,000 volts from line to line and with a frequency of 24 periods per second, an efficiency of 75 per cent. was obtained with a load of about 180 horse-power.

[1] Official Report of the Frankfort Exhibition, ii. p. 451.

CHAPTER XXIX.

REGULATORS FOR DYNAMOS.

MODES of governing the performance of dynamos are needed, not only for keeping the pressure at some constant number of volts or for keeping current at some constant number of amperes, but also for such purposes as to enable the voltage of any one dynamo to be raised in order that it may feed into some distant point of a distributing network.

The output of a dynamo depends on three intrinsic matters, namely, (*i.*) speed n, (*ii.*) number of armature conductors Z, and (*iii.*) magnetic flux N; and on two extrinsic matters, namely (*iv.*) resistance of the circuit; and (*v.*) counter electromotive-forces in the circuit. It is therefore clear that any one of these five matters might afford a method of controlling the performance of the machine.

To introduce resistances into the main circuit is always wasteful, and may be dismissed as an uneconomical method of regulation suitable only for experimental purposes. To introduce counter electromotive-forces into the external circuit can be done in the case of alternate currents by the use of choking coils, and in the case of continuous currents by the reversed introduction of charged secondary cells; but this is impracticable save for special cases on the small scale. It remains therefore to consider the three intrinsic methods.

Speed governing is clearly limited to those cases where there is a separate engine for each dynamo; and in such cases a special governor will be required instead of the usual centrifugal engine governor.

To alter the number of conductors in a rotating armature whilst it is running is absurd. Their *effective* number can, however, be altered by the device of shifting forward the brushes so that they collect the current not at the point of highest potential, but at some other point. This method virtually uses some of the armature windings, namely, those between the neutral point and the point to which the collecting brush is advanced, to produce internal counter electromotive-forces.

To alter the magnetic flux is the almost universal mode of control; and it may be accomplished in two entirely distinct kinds of way. Since the flux depends on the excitation (or ampere-turns) and on the reluctance of the magnetic circuit, it can be varied by varying either the former or the latter. The excitation may be altered in various ways, (*a*) by hand with the aid of rheostats and commutators in the exciting circuit, or (*b*) automatically by special governors in substitution for the hand, or (*c*) by devices of compound winding. The magnetic circuit may be varied in several ways, as (*d*) by moving the pole-pieces nearer to or further from the armature, (*e*) by opening or closing some other gap in the magnetic circuit, (*f*) by drawing the armature end-ways from between the pole-pieces, (*g*) by shunting some of the magnetic lines away from the armature by applying a magnetic shunt across the limbs. All these magnetic devices have been tried,[1] but not with much success except in small machines.

Hand-Regulators.—These consist of sets of sliding contacts to enable the operator to perform one of the following operations:—(1) Insert or remove resistance from the exciting circuit of a shunt dynamo by means of a rheostat[2] (see Edison's regulator, Fig. 152, p. 226); (2) insert or remove resistances, shunting the magnetizing coils of a series dynamo; (3) cut out more or fewer exciting coils, these being grouped in sections.

Constant-pressure and Constant-current Regulators.

In all automatic regulators there is a part which has to act as the brain of the instrument, watching as it were against any variation, and setting into action the mechanism which is to counteract the variation. This watching device is usually some sort of an electromagnet, often a coil with a movable plunger. When the volts are to be kept constant the coil of the controlling device must be wound as a voltmeter coil, that is of fine wire, of

[1] For an example of (*d*) see Firth's method (see *Industries*, ix. 161), in which the polar masses are drawn backwards by screws; and of (*g*) a magnetic shunt applied by Desroziers, *La Lumière Electrique*, xxiv. 394. Other magnetic methods have been used by Goolden and Trotter, Langley, P. Müller, Lontin and Diehl.

[2] On the construction of such rheostats, choice of wires, and the like, see Herrick, *Electrical World*, xv. 240, 1890. Important advances have lately been made in the introduction of *enamelled* resistances, for the first of these operations. Fleming has devised special rheostats for absorbing power in wires strained over resilient supports.

high resistance, and connected as a shunt. When the amperes are to be kept constant the controlling coil must be wound like an amperemeter with thick wire, of low resistance, and inserted in the main circuit. Alternators are usually regulated by operating on the circuit of their exciters, the current in the governor coil being derived from the mains by a small transformer.

Automatic regulators are of two species: in one the work of moving the regulator is accomplished mechanically, the control only being electrical; in the other both the control and the moving power are obtained electrically. Goolden's regulator, which was illustrated in the previous edition of this book, belongs to the former of these classes. The sliding piece of the rheostat is worked by a vertical screw, and this is caused to rotate right or left-handedly as may be required under the operation of a double crown-wheel on a sleeve on the vertical spindle to which rotation is imparted by a small pulley driven slowly from the engine. The controlling part—the brain of the apparatus—is a solenoid with suspended iron plunger. When the current in this coil is of proper normal strength the plunger is drawn in just so far that the crown-wheel is not in gear either with the upper or the lower driver. If the current in the coil grows weak the plunger rises, causing the crown-wheel to engage in the upper driving screw, which immediately begins to move the sliding-contact in such a way as to increase the excitation of the dynamo, and bring back the current in the coil to its normal strength. Slater Lewis has lately introduced a differential solenoid arrangement into the regulator.

An example of the second kind of regulator is that of Maquaire, in which the moving as well as the controlling mechanism is electrical. The moving mechanism is a small motor made reversible by the device explained on p. 519. The controlling mechanism is virtually a relay, consisting of an electromagnet with its armature balanced by a spring.

If the main pressure becomes too low the tongue of the governing relay rises, and touching one of the contact-stops, causes the motor armature to turn so as to alter the resistance and increase the excitation of the dynamo.

In Fig. 513 is shown an automatic regulator of the first kind, designed by Thury and manufactured by the Allgemeine Co., of Berlin. The vertical relay is shown on the left: it actuates one or other of two horizontal coils which throw into gear one or other of the two bevel wheels that drive the worm which turns the rheostat arm. The pulley on the end of the driving shaft must be driven slowly from the engine; or in emergency may be turned by hand.

A simple example of the purely electric regulator is afforded by that of Brush (Fig. 514) by which a series dynamo is made to yield a constant current. Across the field-magnets F. M. is connected a carbon shunt C of variable resistance, the resistance of the shunt being adjusted automatically by a governing electromagnet B whose coils form part of the main circuit.

When traversed by the normal current it attracts its armature A with a certain force just sufficient to keep it in its neutral position.

FIG. 513.—THURY'S REGULATOR.

If the current increases, the armature is drawn upwards and causes a lever to compress the column of carbon plates; the current thus being diverted to a greater or lesser extent from the field-magnets. This regulator will keep the current constant even though the speed of driving may be irregular.

Another purely electrical regulator is that used with the Thomson-Houston arc-light dynamo (p. 463).

In Statter's regulator the brushes are shifted by a motion derived

mechanically from the rotation of the dynamo, but electrically controlled.

The method of regulating Parson's turbo-alternator was described on p. 625.

A regulator devised by Waterhouse employs a third brush upon the commutator to carry a variable portion of the current around a special circuit. It was illustrated in the previous edition of this book, as were also the regulators of Henrion and of Sperry.

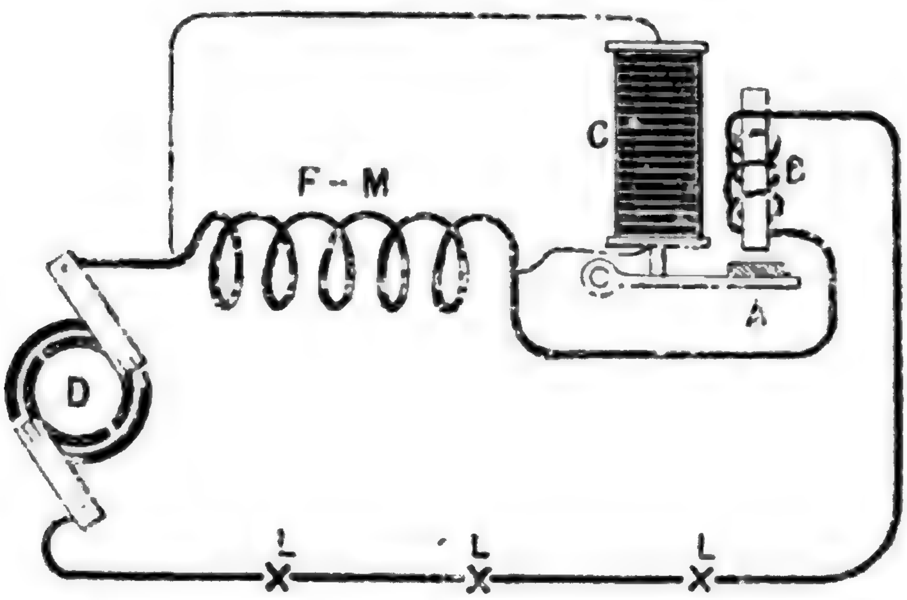


FIG. 514.—BRUSH'S AUTOMATIC REGULATOR.

A special study of this method of regulation has been made by Caldwell,[1] who has shown that it can also be applied to constant-pressure regulation.

For constant-current work Wood has devised a regulator in which a pilot brush is also employed, but there are two exciting circuits wound differentially, and there is an electromechanical device for shifting the brushes, attached to the dynamo. It was depicted in the former edition.

An interesting example of the use of a magnetic shunt to produce a constant current, occurs in the regulator of Trotter[2] and Ravenshaw, in which, instead of diverting the magnetic lines out of their usual path, into a path of lower magnetic reluctance by employing a movable keeper of iron, the plan is adopted of fixing the keeper and varying its effect by surrounding it with a counter magnetizing coil.

[1] *Electrician*, xxii. 217, 1888; and remarks by Professor Nicholls, *ibid.*, 441, 1889.

[2] See paper by A. P. Trotter, in *Electrician*, xix. 374, 1887. A drawing of the governor itself is given in the *Electrical Review*, xix. 289, Sept. 17, 1886.

M. Reignier[1] has drawn attention to a solution of the problem of exact governing to procure a constant current by automatically varying the number of coils through which the current is permitted to pass.

Electric Governors for Steam-engines.

No centrifugal governor attached to the steam-engine can keep the speed of the dynamo truly constant; for it does not act until the speed has become either a little greater or a little less than the normal value. Few mechanical governors will keep the speed within 5 per cent. of its proper value, under sudden changes of load. Hence the suggestion which underlies all electrical governors, that the admission of steam from the boiler to the engine should be controlled by the electric current itself, the speed of driving being varied according to the demands of the circuit. It is emphatically needed wherever the loads are liable to sudden variations, as in the case of generators for electric railways. Numerous suggestions of a more or less practical nature have been made by Lane-Fox, Andrews, Richardson and others.

Richardson's governor[2] was described in detail and illustrated in the previous edition of this book. More recently Mr. Richardson has described[3] some detail modifications which include the use of a relay controlling a mechanically driven governor so as to regulate the engine to maintain a constant electric pressure at any given distant point in the network of mains.

Willans' governor[4] employs the attraction exerted by a solenoid on an iron core to actuate an equilibrium valve; but the action is indirect, the solenoid core operating on the small valve which controls a hydraulic piston, the latter in turn controlling the large steam valve. The arrangement was depicted and described in the previous edition of the present book. A comparatively small solenoid, actuated by but 0·3 ampere of current and absorbing only about 32 watts of power, may by this use of a hydraulic relay, or by a steam relay valve, bring a force of many pounds to bear upon the main steam valve, and will control with ease an engine of several hundred horse-power.

One great advantage of the electric governor is that it cuts

[1] *La Lumière Électrique*, xxvi. 420, 1887.
[2] See Specification of Patent, No. 288 of 1881.
[3] *Proc. Inst. Civil Engineers*, cxx. pt. ii., 1895.
[4] See Specifications of Patent Nos. 1184, 5291 and 5945 of 1883; also paper by P. W. Willans in *Proc. Inst. Civil Engineers*, lxxxi. pt. iii. 1884–5.

down the consumption of steam to the actual demands made upon the electric circuit, and prevents injury both to the dynamo and to the steam-engine.

Dynamometric Governing. — Another method of governing dynamos is too important to be omitted. The power transmitted along a shaft is the product of two factors, speed and torque.

But the power of a dynamo is measured electrically by the product of its electromotive-force into the current it drives through the circuit. If E stands for the electromotive-force, and C for the current, then

$$E\,C = \text{power (in watts)}.$$

Now we know that, other things being equal, the electromotive-force E of the dynamo is proportional to speed of driving. It follows at once that *the torque will be proportional to the current* C. This at once suggests that a dynamo may be driven so as to give a constant current, provided it be driven from a steam-engine governed *not by a centrifugal governor to maintain a constant speed, but by a dynamometric governor to maintain a constant torque or turning moment.* Some good transmission dynamometers, such as that of Morin, or one of the later varieties, such as those designed by Ayrton and Perry, or best of all that designed by the Rev. F. J. Smith,[1] may be adapted to work an equilibrium valve, and would fulfil the above condition of governing.

Prof. E. Thomson has suggested the use of a dynamometric apparatus to govern a constant-current dynamo by the method ot shifting the brushes. A description of this governor was given in the second edition of this work.

Governing by Steam-pressure.—It was remarked above that electric power and mechanical power are each a product of two factors. But in an ordinary steam-engine the work per second also consists of two factors, viz. speed of piston and steam-pressure; and the angular velocity of the shaft is proportional to the former, and its transmitted torque to the latter. Therefore the condition of maintaining a constant current ought to be fulfilled if the pressure is always constant. If the valves are such as to admit a fixed quantity of steam at each stroke, and if the boiler pressure is really kept up, then the average pressure behind the piston ought to be constant. In practice this is never attained, on account of the friction of the steam against the steam-pipes and port-holes of the valves. The internal friction in the engine plays the same part in

[1] See his excellent little book on *Work-measuring Machines*, published by Messrs. E. and F. N. Spon.

preventing absolutely true self-regulation, as does the internal electrical resistance in the dynamo. An approximation is all that is possible.[1] In an experiment made by M. Pollard with a Gramme dynamo, the current gave deflections on a galvanometer, varying only from 52° to 54°, while additional resistances were introduced into the circuit, which caused the speed to run up from 436 to 726 revolutions per minute. Theoretically, therefore, a constant current ought to be one of the easiest things to maintain with a series dynamo. Have adequate boilers, keep the steam-pressure always at one point, abandon all governors, and admit equal quantities of steam at each stroke whatever the speed; the result *ought* to be a constant current. The condition of maintaining a constant potential cannot be similarly solved, except by employing a shunt dynamo under conditions that are both uneconomical and impracticable. But in the case of constant-current working it is possible to go further toward realising such results. The existing method of maintaining a constant steam-pressure is to put upon the boiler a pressure-gauge which indicates to the stoker when he is to add more fuel and when to damp down the fire. Let the pressure-gauge be abandoned, and instead, let there be provided at the side of the furnace an amperemeter, and let the stoker feed or damp his furnace fires according to the requirements of the electric system of distribution. Is there any valid reason why such a method of government should not be efficient in practice, at least in the case of the series dynamo for constant currents?

Finally, to render the system truly automatic, it is conceivable that mechanical stoking appliances might be arranged, under the control of the amperemeter or voltmeter, to supply the fuel in proportion to the number of lamps alight. In the case of gas engines or oil engines such a control would be very easily carried out.

[1] See Edmunds in *Journal Soc. Teleg. Engineers*, xvii. 697, 1888; also *Electrician*, xxii. 349, 422, 1889.

CHAPTER XXX.

TESTING DYNAMOS AND MOTORS.

TESTS to be applied to dynamos are of two kinds, viz. those which relate to the resistance and insulation of the various parts, and those which relate to the efficiency under various loads.

Testing Construction.—The resistance of the various parts of the armature coils, of the field-magnet coils, and of the various connexions, may be tested in the ordinary manner, by means of a Wheatstone's bridge. The only point of difficulty lies in measuring such small resistances as those of armatures and of series coils, which are often very small fractions of an ohm. In this case probably the best method of proceeding is the following. By means of a few accumulator cells send a strong current through the coil or armature whose resistance is to be measured, interposing in the circuit an amperemeter. While this current is passing, measure, by means of a sensitive voltmeter, the fall of potential between the two ends of the coil. By Ohm's law, the number of volts of fall of potential divided by the number of amperes will give the resistance in ohms. Additional accuracy may be secured by connecting in the circuit a strip of stout German silver, as recommended by Lord Rayleigh, of known resistance, and comparing the fall of potential between the two ends of the strip with the fall of potential in the coil. The ratio of the two falls of potential will equal the ratio of the resistances.

The internal resistance of a dynamo when warm after working for a few hours is considerably higher than when it is cold. Tests of resistance ought therefore to be made both before and after the dynamo has been running. The perfection

of the magnetic circuit may be tested in two ways. One way is to measure the proportion of magnetic leakage inductively (p. 153). The other way is to join up a known suitable resistance to the terminals of the machine, and then to run it slowly, gradually increasing the speed until it excites itself. (The method is of course inapplicable to many alternate-current machines.) The least speed of self-excitation is, *cæteris paribus*, a measure of the goodness of the magnetic circuit.

Testing Insulation-resistance.—The rational mode of testing the insulation in the workshop is to apply a high voltage—say from 2000 to 4000 volts—and see whether the insulation resists being pierced. The electric tension or stress to which the dielectric is subjected, tending to pierce it, varies as the square of the volts. The most convenient way of applying the test is to use a small alternate-current transformer giving the requisite voltage. All dynamos, motors and transformers intended for high voltage work should be tested at double the volts which they are intended to work at. Tests of the insulation-resistance between the coils of a dynamo and its metal cores or frame by use of a Wheatstone's bridge, made regularly day by day, are only useful as far as they serve as a guide to the way in which the machine is being cared for; since damp and dirt lower the insulation, and if neglected promote likelihood of a break-down.

Testing Temperature-rise.—The instructions given by the Admiralty for tests of temperature are as follows:—

"At the end of a six hours' trial, and one minute after stopping the machine, no accessible part of the armature or field-magnet must have a temperature of more than 30° Fahr. above that of the dynamo room, taken on the side of the dynamo remote from the engine, and three feet distant from it. Also the maximum temperature of the armature at the end of the six hours' trial must not exceed the temperature of the dynamo room by more than 70° Fahr." It is usual to employ thermometers with narrow cylindrical bulbs which can be inserted in the armature, or laid upon it and covered with a pad of cotton wool while the test is made.

Testing Performance and Efficiency.—The testing of the efficiency and working capacity of a dynamo, whether working as generator or as motor, is a more serious matter, and involves both electrical and mechanical measurements.

In the case of the dynamo generating currents, measurements must be made (*a*) of the mechanical input and (*b*) of the electrical output.

In the case of the motor doing work, measurements must be made (*a*) of the electrical input, and (*b*) of the mechanical output.

Measurement of Power.—The general methods of measuring the power mechanically are as follows:—

(*a.*) *Indicator Method.*—By taking indicator diagrams from the steam-engine which supplies the power.

(*b.*) *Brake Method.*—By absorbing the power delivered by the machine, at a friction brake such as that of Prony, Poncelet, Appold, Raffard, or Froude.

(*c.*) *Dynamometer Method.*—By measuring in a transmission dynamometer or ergometer, such as that of Morin, von Hefner-Alteneck, Ayrton and Perry, or of F. J. Smith, the actual mechanical power of the shaft or belt.

(*d.*) *Balance Method.*—By balancing the dynamo or motor on its own pivots and making it into its own ergometer.

(*e.*) *Electrical Method.*—By making the motor drive the dynamo which supplies it, measuring electrically the work given out in the one, or absorbed by the other, and then measuring, either mechanically or electrically, the difference.

(*f.*) *Steam Consumption.*—In cases where indicators cannot be used (as for example in tests of steam turbines), the weight of steam consumed per hour, as measured by feed-water supplied to the boiler or by the water from the condenser, may be taken as a measure of the gross power.

(*a.*) *Indicator Method.*—The operation of taking an indicator diagram of the work of a steam-engine is too well known to engineers to need more than a passing reference. It measures the gross power imparted thermally to the engine, not the nett power given by the engine to the dynamo. This method is, however, not always applicable, for in many cases the steam-engine has to drive other

machinery, and heavy shafting for other machinery. In such cases the only remedy is to take two sets of indicator diagrams, one when the dynamo is at work, the other when the dynamo is thrown out of gear, the difference being assumed to represent the horse-power absorbed by the dynamo.

(*b.*) *Brake Method.*—The friction brake of Prony is well known to engineers, but the same can hardly be said of the more recent forms of friction dynamometers. Various improvements have been introduced in detail from time to time by Poncelet, Appold, and Deprez. In Prony's method the work is measured by clamping a pair of wooden jaws round a pulley on the shaft; the torque on the jaws being measured directly by hanging weights on a projecting arm with a sufficient moment to prevent rotation. If p is the weight which at a distance l from the centre balances the tendency to turn, then the friction force f multiplied by the radius r of the pulley will equal p multiplied by l.

This may be written,

$$\text{Torque} = f\,r = p\,l.$$

From which it follows that

$$f = \frac{p\,l}{r}.$$

If n be the number of revolutions *per second*, then $2\,\pi\,n$ is the number of radians per second, or in other words, the angular velocity, for which we use the symbol ω, and $2\,\pi\,n\,r$ is the linear velocity v at the circumference. Now the work per second, or power, is the product of the force at the circumference into the velocity at the circumference, or

$$w = f\,v = \frac{p\,l}{r}\,.\,2\,\pi\,n\,r = 2\,\pi\,n\,p\,l.$$

If p is measured in pounds' weight, and l in feet, then, remembering that 550 foot-pounds per second go to one horse-power, we have,

$$\text{horse-power absorbed} = \frac{2\,\pi\,n\,p\,l}{550};$$

or, if p is expressed in grammes' weight, and l in centimetres, it must be divided by $7 \cdot 6 \times 10^6$ to bring it to horse-power.

The latter improvements imported into the Prony brake are of great importance. Poncelet added a rigid rod at right angles to the lever, and attached the weights at the lower end. Appold substituted

for the wooden jaws a steel strap, giving a more equable friction, and therefore having less tendency to vibration. Raffard[1] substituted a belt differing in breadth, and therefore offering a variable coefficient of friction, according to the amount wrapped round the pulley. Further modifications of this kind of brake dynamometer have been made by Professor James Thomson, Professor Unwin, M. Carpentier, and by Professors Ayrton and Perry. The friction of a turbine wheel was also applied as a dynamometer brake by the late W. Froude. Professor Alex. B. W. Kennedy has obtained excellent results from the use of a rope brake.

As all these brake dynamometers measure the work by destroying it, it will be seen that though they are admirably adapted to measure the work furnished by a motor, they cannot, except indirectly, be applied to measure the work supplied to a dynamo. Some experience in working with these machines is essential if reliable results are to be obtained; but with the more modern forms of instruments, such as those of Poncelet and Raffard, the results are very good. The great secret of success is to keep the friction surfaces well lubricated with an abundant supply of soap and water.

Probably the most accurate method of measuring power by absorbing it is to use as brake a dynamo of high and known efficiency on a load of lamps, the output being measured by amperemeter and voltmeter.

(*c.*) *Dynamometer Method.*—The Prony brake was styled above a brake dynamometer; but the true dynamometer for measuring transmitted power does not destroy the power which it measures. Transmission dynamometers may be divided into two closely allied categories: those which measure the power transmitted along a belt, and those which measure power transmitted by a shaft.

In the case of transmitting power by a belt, the actual force which drives is the difference between the pull in the two parts of the belt. If F' is the pull in the slack part of the belt before reaching the driven pulley, and F the pull in the tight part of the belt after leaving the driven pulley, then $F - F'$ represents the nett pull at the

[1] For further accounts of these instruments the reader is referred to Weisbach's *Mechanics of Engineering*; Spons' *Dictionary of Engineering*, Article "Dynamometer"; Smith's *Work-measuring Machines*; a series of articles in the *Electrician*, 1883–4, by Mr. Gisbert Kapp; *Proc. Inst. Mech. Eng.*, 1877, p. 237 (Mr. Froude); *Rep. Brit. Assoc.*, 1883 (Prof. Unwin); *Journ. Soc. Telegr.-Eng. and Electr.*, vol. xii. p. 346 (Profs. Ayrton and Perry). See also *Official Report* of the Electrotechnical Exhibition of Frankfort, 1891, for the brake tests made on the turbines at Lauffen.

circumference, and $(F - F') \times r$ is the torque T. Then if n is the number of revolutions *per second* the angular velocity ω will be equal to $2 \pi n$. This gives us as the work per second, or power,

$$w = \omega T = fv = 2 \pi n r (F - F').$$

As before, if F is expressed in pounds' weight and r in feet, the expression must be divided by 550 to bring to horse-power; or must be divided by $7 \cdot 6 \times 10^6$ if the quantities are expressed in grammes' weight and centimetres.

A dynamometer which can be applied to a driving belt, and actually measures the difference $F - F'$ in the tight and slack parts of the belt, has been designed by von Hefner Alteneck, and is commonly known as Siemens' belt dynamometer.[1] Other forms have been devised by Sir F. J. Bramwell, W. P. Tatham,[2] W. Froude, T. A. Edison and others. Nearly all of these instruments introduce additional pulleys into the transmitting system, causing additional friction.

Much more satisfactory are those transmission dynamometers which measure the power transmitted by a shaft. In nearly all instruments of this class there is a fixed pulley keyed to the shaft, and beside it a loose pulley connected with it by some kind of spring arrangement, so set that the elongation or bending of the spring measures the angular advance of the one pulley relatively to the other; this angular advance is proportional to the transmitted torque. To this class of instrument belongs the well-known dynamometer of Morin, in which the displacement of the loose pulley is resisted by a straight bar spring, the centre of which is attached to the driving shaft. Modifications of the Morin instrument have been devised by Easton and Anderson, Heinrichs,[3] Ayrton and Perry,[4] Murray,[5] and the Rev. F. J. Smith, of the Millard Engineering Laboratory, Oxford. Of the last named instrument, a full description and cut were given in former editions of this book.

(*d.*) *Balance Method.*—With small motors there arises the difficulty that the ordinary means of measuring the work they perform introduce relatively large amounts of extraneous friction. The motor

[1] One form of the Siemens dynamometer is described by Hopkinson, *Proc. Inst. Mechan. Eng.*, 1879. A more modern form is described by Schroter, *Bayerisches Industrie- und Gewerbeblatt*, 1883.

[2] *Journ. Franklin Institute*, Nov. 1886.

[3] See *Engineering*, May 2, 1884, and *Electrical Review*, April 26, 1884.

[4] *Journ. Soc. Telegr.-Eng. and Electr.*, xii. 163, 1883. [5] *Ibid.*, xviii. 1889.

to be tested is placed with its armature spindle between centres, or on friction wheels, and the weight of the field-magnets and frame is very carefully balanced with counterpoise weights. In Fig. 515, B D represents the field-magnets and frame of the motor duly counterpoised, and E is the armature. When the current is turned on, the armature tends to rotate in one direction and the field-magnets in the other; the angular reaction being of course equal to the angular action. If the reaction which tends to drive the field-magnets round be balanced by applying a force P (for example that of a spring balance) at the point C of the frame A B C D, then the moment of this force, P *d*, measures the torque, exactly as in the Prony brake. Hence it will be seen that the motor has become its own dynamometer, the magnetic friction between the armature and the field-magnet being substituted for the mechanical friction between the

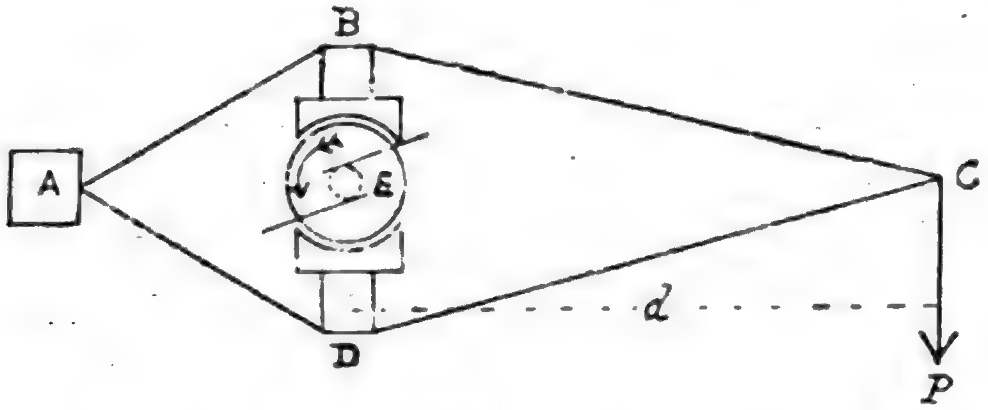


FIG. 515.—REV. F. J. SMITH'S METHOD OF TESTING MOTORS.

pulley and the jaws. A modification of the balance method, due to Herman Müller, consists in swinging the dynamo in a cradle, pendulum fashion, from the driving shaft, and estimating the power absorbed by the displacement from the vertical line.

M. Marcel Deprez and Professor C. F. Brackett have proposed to apply the balance method to dynamos in action. Professor Brackett places the dynamo in a sort of cradle, balanced on centres that lie in the axis of rotation, and measures the torque between the armature and field-magnets, and multiplying this by the angular velocity $2 \pi n$, obtains the value of the power transmitted to the armature.

All these several dynamometric methods necessitate the use of a speed-indicator to count the number of revolutions n, which enters as a factor into the calculation of horse-power. The number of revolutions *per second* n being known, the angular velocity $\omega = 2 \pi n$ can be calculated. This only requires to be multiplied by the torque

$T = Fr$ to give the power or work-per-second w. And if T is expressed in pound-feet, then,

$$\text{horse-power} = \frac{2\pi n F r}{550} = \frac{\omega T}{550}.$$

(*e.*) *Electrical Methods.*—There are several varieties of this modern method of testing, and they involve the use of two or in some cases three machines. Two machines, one to act as generator, the other as motor, are connected together both electrically and mechanically, so that the power is *circulated* between the two machines, passing from generator to motor electrically, and returned from motor to generator mechanically. The power given out by the generator machine, and that absorbed by the motor, are measured electrically. In the original plan of Dr. J. and E. Hopkinson,[1] the small additional power required to drive the generator was supplied by a steam-engine and measured mechanically by a dynamometer. By thus circulating the power it is possible to test a pair of machines at say 500 horse-power each, using only a 50 horse-power steam-engine. Modifications of this method for the purpose of obviating all mechanical measurements have been suggested by Lord Rayleigh,[2] Major Cardew,[3] whose method dates from 1882, M. Menges,[4] Mr. Ravenshaw[5] and Mr. Swinburne.[6]

All these methods are far more accurate than the rough mechanical methods of earlier date, and each has its advantages, but Hopkinson's method requires two similar machines, and Cardew's requires three machines, one of which must be powerful enough to run the other two. In Swinburne's method the loss of power due to resistance of conductors is calculated, and this deducted from the whole loss of power in the machine gives the "stray power" made up of losses due

[1] *Phil. Trans.*, 1886, ii. 347. See also *Electrician*, xvi. 347, 1886; and *Electrical Review*, xviii. 207 and 230, 1886.

[2] *Electrical Review*, xviii. 242, 1886.

[3] *Ibid.*, xix. 464, 1886; and *Electrician*, xvii. 410, 1886; and xxi. 275, 1887.

[4] *Electrician*, xvi. 371, 1886.

[5] *Electrical Review*, xix. 424 and 437, 1885.

[6] *Ibid.*, xxi., 181 and 215, 1887.

to eddy-currents, friction and magnetic hysteresis, which are thus measured together. This stray power is determined by using the machine as a motor, the field-magnets being separately excited so that the armature has the same magnetic induction as at full load, the electromotive-force applied to it being such as to drive it at its normal speed. Only a small generating dynamo is required to furnish the current for this. When matters are so arranged that the machine to be tested runs at its normal speed, the power used in driving the machines (which is measured electrically by taking readings of the volts on the armature and the amperes flowing through it, and multiplying up) is equal to the stray power at full load.

An example may be useful. Suppose we have to test a large 50 kilowatt shunt-wound dynamo, giving 500 amperes at 100 volts at 720 revolutions per minute, and that $r_a = 0{\cdot}006$ ohm, and $r_s = 12$ ohms, the lost amperes will be $100 \div 12 = 8{\cdot}5$, total current say 508 amperes; hence lost volts $508 \times 0{\cdot}006 = 3$ volts; whence $E = 103$ volts. Watts lost in armature $= 508 \times 508 \times 0{\cdot}006 = 1548$. Watts lost in shunt coil $= 100 \times 100 \div 12 = 833$. Now arrange any small dynamo, of say 2 H.P., to give out current at 103 volts; and from this run the large dynamo that is to be tested, as a motor, with no other load than its own friction, hysteresis and eddy-currents. It will run under 720 revolutions, since with such small current its armature produces no demagnetizing action to quicken it up. Therefore add some resistance to its shunt till it comes up to speed. Then measure the current it is taking; this multiplied by E gives the stray power. Suppose it takes 9 amperes, then the stray power is $103 \times 9 = 927$ watts. We may at once reckon out the efficiencies. The losses now known are $1548 + 833 + 927 = 3308$. Add this to the 50,000 watts of nett output, and we get the gross output 53,308. Hence we have the following:—

$$\text{Gross efficiency} = \frac{52381}{53308} = 98{\cdot}3 \text{ per cent.}$$

$$\text{Electrical efficiency} = \frac{50000}{52381} = 95{\cdot}5 \quad ,,$$

$$\text{Nett efficiency} = \frac{50000}{53308} = 93{\cdot}8 \quad ,,$$

Mr. Kapp[1] has devised a method of testing which permits the commercial or nett efficiency to be determined electrically with far higher accuracy than is possible with any mechanical dynamometer. It requires two machines of nearly equal power, one G to run as generator, the other M as motor, together with a small auxiliary machine X of normal voltage, to which the

[1] See *Electrical Engineer*, Jan. 22, 1892, and *Electrician*, July 5, 1895, 319.

other two are coupled in parallel, Fig. 516. The armatures of G and M must also be coupled together mechanically, and the field of M must be weakened by use of a rheostat, so that it may run as a motor. X gives the current necessary for exciting and for making up the difference between the currents in G and M. Insert an amperemeter from one brush of G to one of M to measure the current. Take a reading of the G current when the auxiliary current is led in on the right, and another reading of the M current when the auxiliary current is led to the left. As the volts are the same in each case, the ratio of the two currents is the efficiency of the combination of the two machines; and the square root of the ratio of the two readings is the efficiency of either machine.

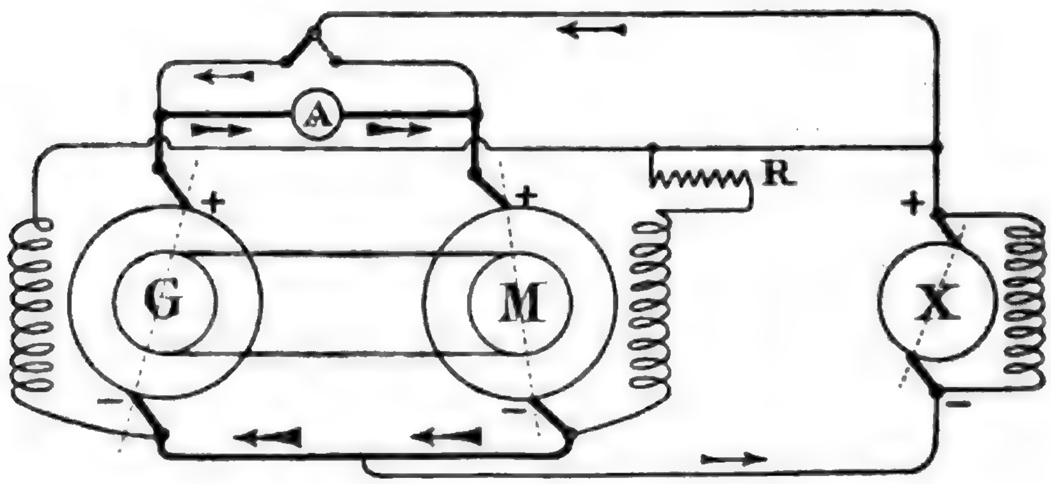


FIG. 516.—KAPP'S METHOD OF TESTING EFFICIENCY.

Testing Separate Losses.—In the preceding paragraph no distinction was made between the three sources of loss which go to make up the stray power, namely, friction, eddy-currents and hysteresis. It was indeed possible to separate the eddy-current loss from the others by making experiments at different speeds,[1] because the eddy-current loss increases proportionately to the square of the speed, whilst the other losses are approximately proportional simply to the speed. The power thus wasted was given to the armature by a motor and measured electrically. In 1891, a method of separating these losses was independently published by Kapp[2] and

[1] *Journ. Inst. Electrical Engineers*, xviii. 620, 1889.
[2] *The Electrician*, xxvi. 699, 1891.

by Housman.[1] From the latter's paper is taken Fig. 517, which shows the method adopted by both these engineers. The method is as follows:—Let the field-magnet be separately excited to a constant value. Then measure the currents required to run the armature as a motor with no load at different speeds, by using different volts. The results when plotted out as a curve give a straight line A B, Fig. 517, cutting the axis of current above the origin. A horizontal line A D, through A, divides the ordinates, such as C B, into two parts; one C D, which represents the losses that are propor-

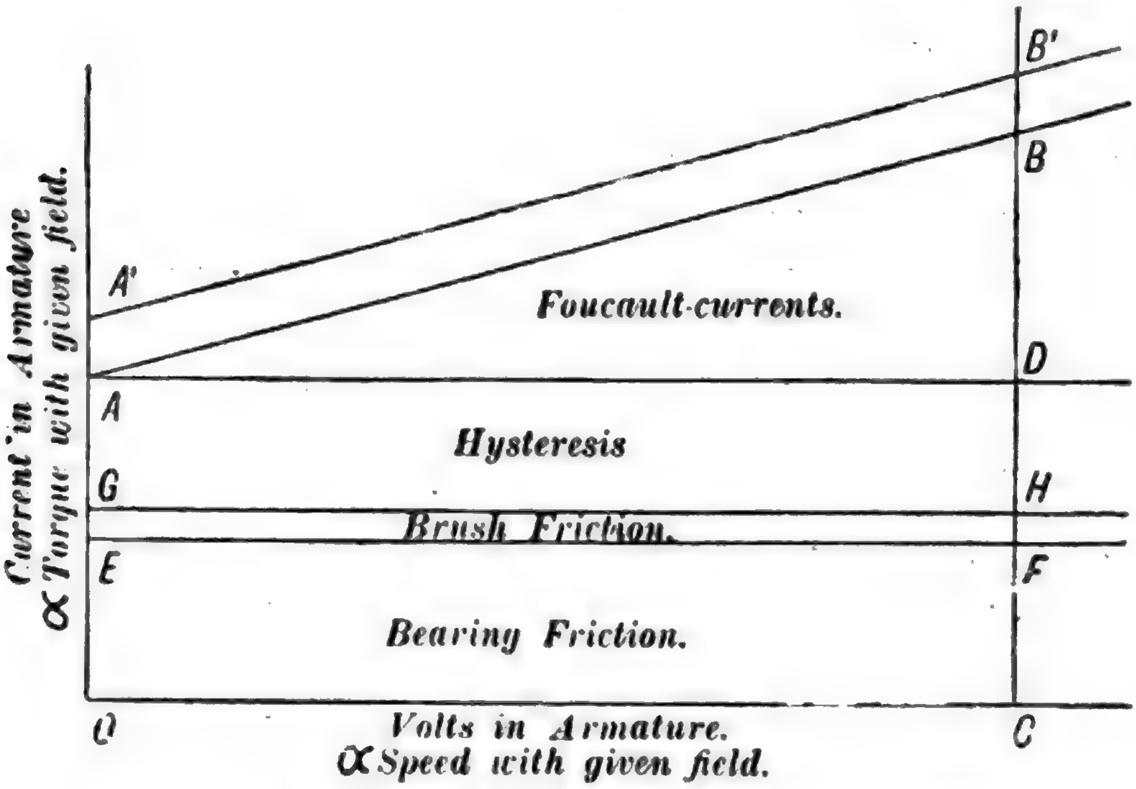


FIG. 517.—SEPARATION OF LOSSES IN DYNAMO.

tional to speed; and another D B which represents those that are proportional to the square of the speed. To separate friction of bearings and brushes, the armature should be coupled direct to another similar machine, the latter running without excitation of magnets, when the increase of current needed to drive will give a measure of frictional loss, and from this the lines E F and G H may be plotted out. If a second set of observations are made with a field of different strength, a second line A' B' will be obtained, which will be above or

[1] *Ibid.*, xxvi. 700, 1891; also *Journ. Inst. Electrical Engineers*, xx. 298, 1891.

below A B, according to whether the change of field has increased or diminished the total losses. The minimum total loss usually occurs with an excitation that makes the flux-density B in the armature about 15,000 or 16,000; for when the excitation is pushed further, not only does hysteresis become much greater, but the eddy-currents in shaft and pulley due to the leakage of magnetic lines are greater. If the line A B curves upwards at the higher values, it shows that the eddy-currents in the armature are producing perceptible demagnetization.

Testing of Combined Plant.—It is usual to specify for combined plant that the efficiency of the combined engine and dynamo taken together, on a run of several hours at full load, shall reach some prescribed figure; and that the steam consumption per kilowatt-hour of output shall also not exceed a given limit. The requirements of British consulting engineers have been for many years exacting, with the result that manufacturers and contractors [1] have attained to exceedingly high efficiencies.

As an example of tests of a continuous-current combined plant we may take those made by Professor A. B. W. Kennedy in May 1893, at Thames Ditton, of a 123 kilowatt shunt-wound dynamo by Holmes & Co., direct driven from a two-crank compound Willans engine (condensing) at 335 revolutions per minute. During a six hours' run with a load of 1010 amperes at 120 volts (or 121·5 kilowatts, or 162·8 horse-power electrical output), steam was being used at 3314 lbs. per hour, or 27·3 lbs. per kilowatt hour, or 20·3 lbs. per horse-power hour, of the nett electrical output. The internal horse-power during same time, as measured with indicators, was 190·2, giving an efficiency of 85·6 per cent. The steam used per horse-power indicated was 17·4 lbs. The rise of temperature at the end of the run was found to be 40° C. above that of the surrounding air. Tests were made also at $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ load, also when the dynamo was run on open circuit, excited and unexcited, and when the engine was run alone uncoupled.

[1] See a remarkable paper by Mr. R. E. Crompton, *Proc. Inst. Civil Engineers*, vol. cvi. 1891.

The results are plotted out in the accompanying diagram, Fig. 518. When worked out in detail it appears from these tests that the efficiency of the engine by itself is 89·5 per cent.; that of the dynamo by itself 95·6 per cent.

The elaborate tests of Parsons' steam turbine (p. 625), made by Professor Ewing in 1892 showed a steam consumption of 27 to 28 lbs. per kilowatt hour at full load, and of 30 to 32 lbs. per kilowatt hour at half load; still higher results being claimed for the recent steam turbines of larger size.

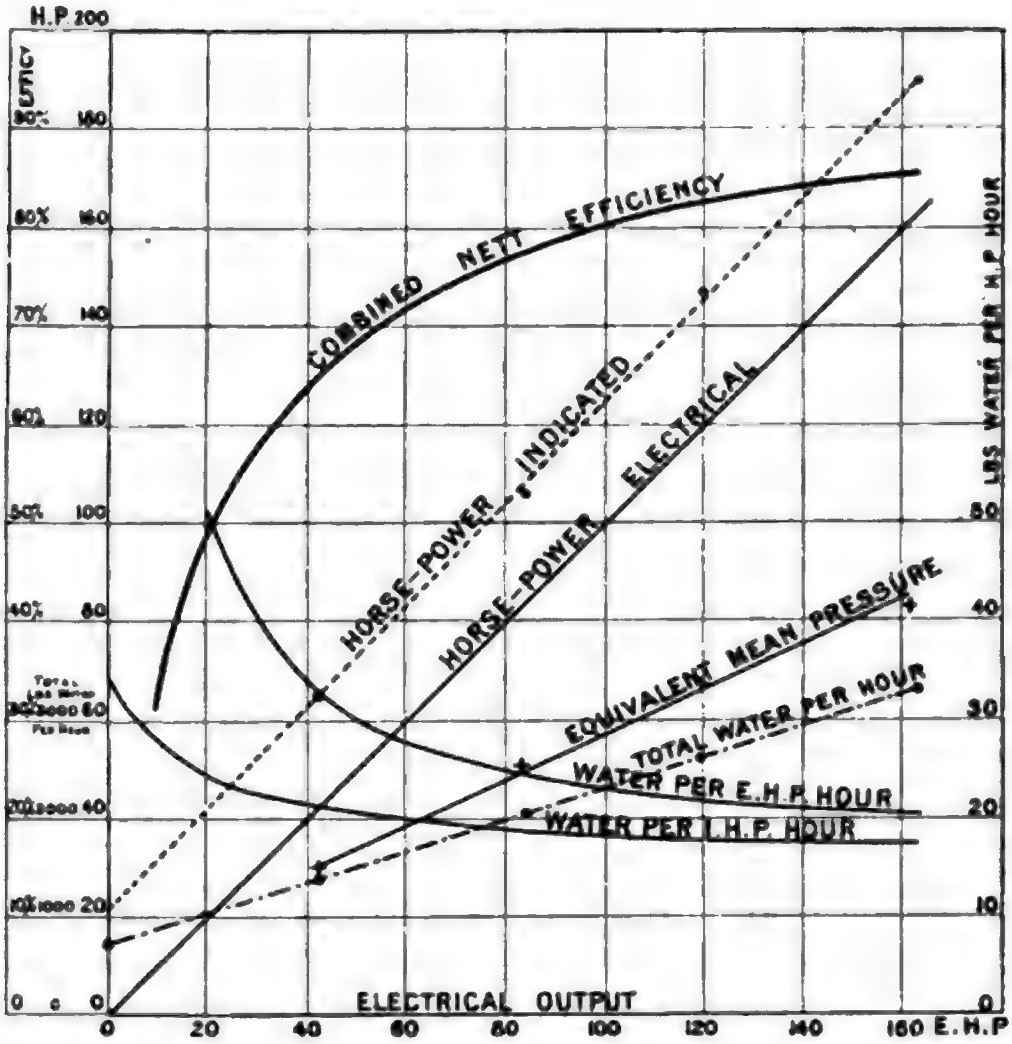


FIG. 518.—TEST OF HOLMES-WILLANS COMBINED PLANT (KENNEDY).

An elaborate arrangement of speed-cones for dynamo-testing, designed by Prof. Ayrton, is described in *Industries*, June 22, 1888. For detailed accounts of tests on dynamos the reader is referred to the following sources :—*Report of Committee of Franklin Institution*, 1878; *Official Report of Munich Electric Exhibition*, 1882; also Prof. W. G. Adams' Inaugural Address, *Journal of Society of Telegraph-Engineers and Electricians*, xiv. 4, 1885; also Reports of Electrical Exhibition at Philadelphia, 1884, published in *Journal of the Franklin Institution*, 1885; tests of arc-lighting dynamos at Melbourne Exhibition, by

K. L. Murray, *Journal Institution Electrical Engineers*, xviii., 1889; tests of dynamos (Desroziers, Edison, Gramme, &c.) at Paris Exhibition of 1889, by A. Minet, *La Lumière Électrique*, xxxv. 1889; tests on Stanley Arc Alternator by Duncan and Hassen, *Electrician*, xxvi., Jan. 1891; tests of a Goolden dynamo and Willans engine, separating the losses, *ib.* xxvi. p. 36, 1890; tests of a Wenström dynamo, separating the losses, by Duncan, *Electrical Review*, xxvi. 116, Jan. 1890; papers on Causes of Losses, by Hummel, in *Elektrotechnische Zeitschrift*, viii. 1887, and xii. 1891. At the Frankfort Exhibition of 1891, very careful tests were made of numerous machines under very favourable conditions. These are detailed in the second volume of the *Official Report*, published at Frankfort in 1893.

CHAPTER XXXI.

MANAGEMENT OF DYNAMOS.

THIS chapter is devoted to three topics:—(1) The coupling of two or more dynamos. (2) General instructions in use of dynamos. (3) The diseases of dynamos.

ON COUPLING TWO OR MORE DYNAMOS IN ONE CIRCUIT.

It is sometimes needful to couple two or more dynamos together so that they may supply to a circuit a larger quantity of electric energy than either could do singly. Thus it may occur that two dynamos, neither of which can safely carry a greater current than 1000 amperes, are required to supply jointly a 2000-ampere current: or two machines, each of which can run at 60 volts, are required to furnish an electromotive-force of 120 volts. Simple as these cases may seem, it is not so easy to carry them out, because it depends upon the construction of the machine, and especially upon the mode of excitation of the field-magnets, whether they can be coupled together without interfering with each other's running. For it may, and does, occur that if not rightly arranged, one machine will absorb energy from the other and be driven as a motor instead of adding anything to the energy of the circuit.

Coupling Continuous-current Machines in Series.—Series-wound dynamos may be united in series with one another for the purpose of doubling the electromotive-force. Thus two Brush machines, each working at 10 amperes, and each capable of working 6 arc-lamps, may be joined in one circuit with 12 arc-lamps in series. The only needful precaution is to see that the + terminal of one machine is joined to the – terminal of the other, precisely as with cells of a battery. Shunt-wound dynamos may also be coupled in series, though the arrangement is not good unless the two shunt coils are also put in series with one another, so as to form one long shunt across the circuit. Compound-wound dynamos may be connected in

series with one another, provided the shunt parts of the two are connected as a single shunt, which may extend simply across the two armatures (double short-shunt), or may be a shunt to the external circuit (double long-shunt), or may be a mixture of long and short shunt. The same considerations apply to more than two machines. The coupling of alternate-current dynamos is considered in Chapter XXIV.

Coupling Dynamos in Parallel.—Dynamos, to run well in parallel without any special coupling devices, should have a falling characteristic (see p. 212), for if the characteristic rises, then the machine yielding the greatest share of the current will have its electromotive-force increased thereby and will yield more and more current until it takes all the load and drives the other machines as motors. If, on the other hand, the electromotive-force falls with an increase of current the load is automatically divided between the machines. It is, of course, possible for a machine to have a rising characteristic when run at a perfectly constant speed, and yet through the slowing of the engines with increased load the characteristic of the combined plant may be a falling one. In such a case, where each dynamo is driven by a separate engine parallel working would be possible.[1]

Simple shunt machines always have a falling characteristic and therefore there is no great difficulty in running them in parallel, as indeed is done on a large scale every day in central lighting stations. The chief precaution to be taken is that, whenever an additional dynamo has to be switched into circuit, its field must be turned on, and it must be run at full speed before its armature is switched into connexion with the mains, otherwise the current from the mains will flow back through it and overpower the driving force.[2]

Two series dynamos cannot be coupled in parallel in a circuit without a slight rearrangement, otherwise they interfere. For, suppose one of them to fall a little in speed, so that the electromotive-force of one machine is higher than that of the other machine with which it is in parallel, the machine having the higher electromotive-force will then drive a current in the wrong direction through the other machine, reversing the polarity of its field-magnets and driving

[1] Sayers, *Journ. Inst. Elec. Engs.*, xxiv. 137, 1895.

[2] See Burstyn, in the *Zeitschrift für angewandte Elecktricitatslehre*, 1881, p. 339, also Schellen (2nd edition), p. 717; Ledeboer, in *La Lumière Électrique*, xxvi. 210, 1887; Meylan, in *La Lumière Électrique*, xxvi. 379, 1887; and Feussner, in *Zeitschrift für Elektrotechnik*, 1887, 108; also Prof. Puffer in *Technology Quarterly*, v. 380, 1893. See also the special mode devised by S. S. Wheeler, U.S. Patent, No. 335,048 of 1886.

it as a motor. To obviate this, Gramme made the suggestion that the machines should be coupled in parallel at the brushes as well as at the terminals. This is shown in Fig. 519. The terminals T_1 T_1 of one machine are respectively joined to T_2 T_2 of the second machine, and a third wire joins B_1 with B_2. Triple-pole switches are convenient. If both machines are doing precisely equal work, there will be no current through the wire B_1 B_2. If either machine falls behind, part of the current from the other machine will flow through B_1 B_2 and help to maintain the excitement of the magnets of the weaker machine. This effectually prevents reversals. Another method of coupling two series machines is to cause each to excite the other's field-magnetism. This equalizes the work between the two machines.

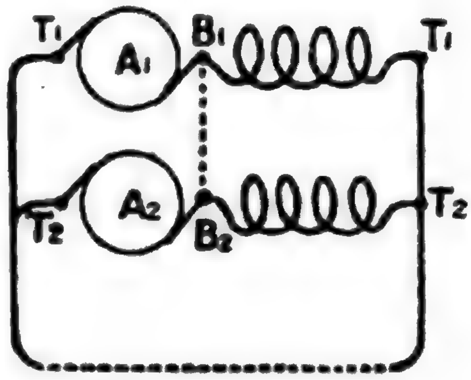


FIG. 519.—COUPLING OF TWO SERIES DYNAMOS IN PARALLEL.

Coupling of Compound Dynamos in Parallel.—In working compound dynamo machines in parallel circuit, some difficulty has been found, on account of their tendency to behave in the same manner as series-wound machines. Mr. Mordey first pointed out that the difficulty might be overcome by connecting the parallel machines in such a way that not only are the shunt portions of the field-magnets in parallel circuit, but the series circuits of the field-magnets are also a shunt on one another; in other words, by connecting the brushes, as well as the terminals, in parallel circuit, precisely as Gramme has done for series-wound machines.

In Fig. 520, A_1 A_2 are the armatures of two compound dynamos, T_1 T_1 and T_2 T_2 are the terminals; the wire B_1 B_2 acting in conjunction with the lead T_1 T_2 on the left, puts the armatures in parallel. The dynamos should each be furnished with a switch s in the shunt circuit; they should each also have a switch m in their main circuit between the armature part and the point where the shunt circuit joins on, so that the armature part may be interrupted without interrupting the shunt circuit. The connecting wire from brush to brush, which should be at least as thick as the mains, should also be furnished with a switch z. Suppose dynamo No. 1 is at work alone, its two switches s m_1, will be closed. If, now, dynamo No. 2 is to be thrown in, the following order must be observed. First get up the speed of No. 2 to its full value, then close s_2, then z; this will fully excite its magnetism; lastly, close m_2. When No. 2 has to be

thrown out of circuit the order must be exactly reversed: first open m_2; then z; then s_2; lastly, slow down the machine. A special combination-switch, which will perform these successive operations in their proper order, is desirable.

When compound dynamos are connected in this way,[1] they work quite satisfactorily, and exercise a considerable power of mutual adjustment; for any increase in the current from one machine is divided equally among the series coils and does not raise the electromotive-force of one machine more than another.

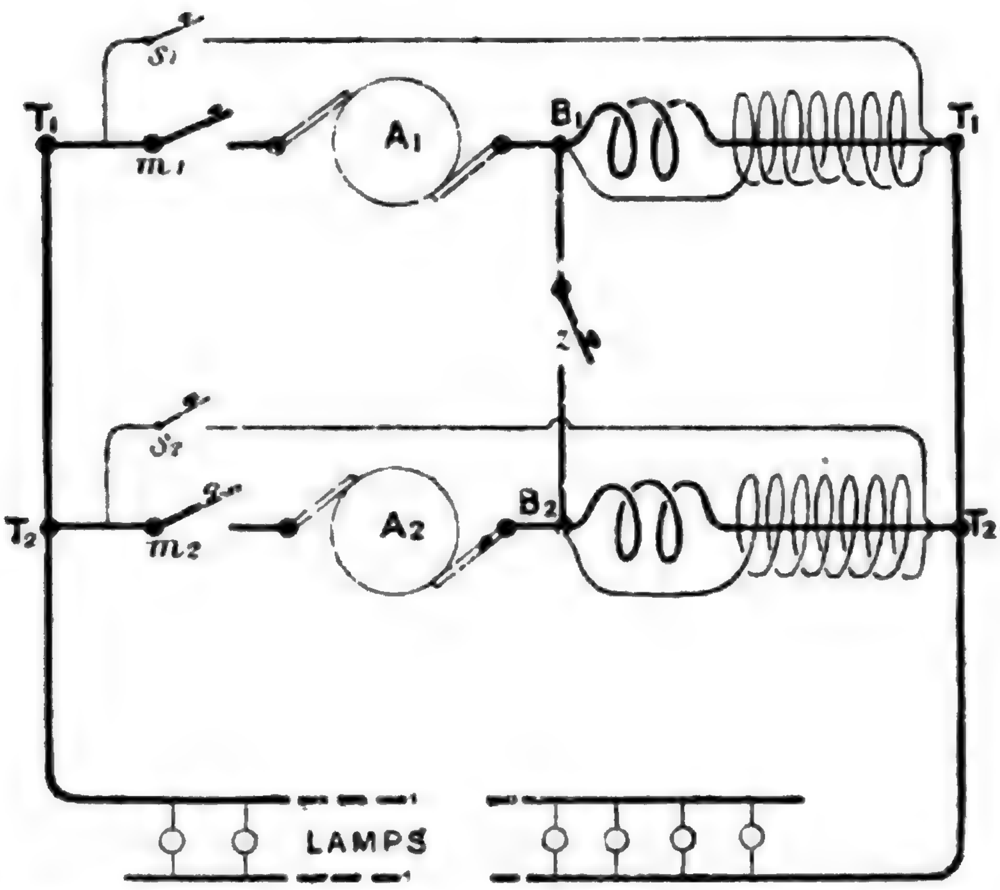


FIG. 520.—COUPLING OF TWO COMPOUND DYNAMOS IN PARALLEL.

Not only does this control exist with similar compound dynamos, but it may be relied on when the dynamos are unlike in size, power and speed. For instance, large and powerful machines may be worked in parallel circuit with smaller machines of various powers, and each will do its proper share of the work. The resistance of the series coil of each machine must, in this case, be adjusted so that the division of the current among the coils is in proportion to the powers of the machines. If the switch z is permanently kept closed the effect is to make the excitation of the field of all the machines depend

[1] The method proposed by M. Ledeboer in *La Lumière Électrique*, xxvi. 210, 1887, is practically identical with the above.

upon the total output of the station, and thus it is possible to compensate for a drop in volts which takes place in the mains.

The usual practice in English central stations, supplying continuous current, is to employ simple shunt dynamos regulated by hand.

The parallel running of alternate-current dynamos is considered in Chapter XXIV.

General Instructions in Use of Dynamos.

Position of Dynamo.—The place chosen should be dry, free from dust and preferably where a cool current of air can be had. It should allow sufficient room for a belt of proper length, unless the dynamo is direct-driven.

Foundations.—It is most important to secure good foundations for every dynamo; and if the dynamo is direct-driven, but is not on the same bed-plate as the engine, a foundation large enough for both together should be laid down. Stone or concrete may be used, or brick built with cement, having a large thick stone bedded at the top. For small dynamos the holding-down bolts may be set with lead or sulphur in holes in the stone top; but for large dynamos the bolts should be long enough to pass right down to the bottom, where they should be secured into iron plates built in. If long holes are left in the foundations for the holding-down bolts, they should be filled in with thin cement after the latter have been put in place.

Sliding Rails.—All belt-driven dynamos ought to be provided with tightening gear to take up the slack. If the dynamo is not provided with sliding rails under its bed-plate, and tightening screws, the less desirable method of employing a tenting pulley, as in Plate IX., may be used. In any case the bed for the dynamo must be quite level, and its shaft set properly parallel with the driving pulley.

Setting up.—Before setting up any dynamo or motor which has been long unused, or has been exposed to changes of climate, it should be kept for a few days in a warm and dry place. For the insulation materials are liable to absorb damp that can only be slowly dried out. Nothing is more likely to cause a break-down than to attempt to run a machine that is not thoroughly dry.

Before Starting.—Examine the dynamo before it is set running for the first time. Remove caps of bearings and clean them and the journals. Replace them, but do not screw up too tightly. See that lubricators are filled, and the drip properly adjusted. Where the

bearings are self-oiling see that the oiling ring works properly. Use *copper* oil-cans. Turn the armature round by hand to see that nothing catches and no loose wires or waste are adhering to it. Clean up the commutator with the finest glass-paper, and note carefully that no dirt or copper-dust is lodged between the bars of the commutator. A stiff dry hog-brush will be useful here. See that the brush-holders work rightly, and that the hold-off catches, if any, are in order. See that each brush is properly trimmed (i. e. filed off at the proper bevel at the ends. Some makers provide a special tool to guide the file at the proper angle). Adjust the brushes, first, by clamping them *very firmly* in their holders, so that they protrude to the proper length. (For this purpose many makers provide a holder with a pointer, as at P on Plate III.) Adjust them, secondly, so that they bear with a moderate but firm pressure on the commutator. See, thirdly, that when so pressing, they bear in the right positions. For 2-pole dynamos the brushes should bear on precisely opposite bars of the commutator. For 4-pole dynamos they bear on bars that are a quarter of the circumference apart. (It is customary for makers to mark two of the commutator bars with a centre-punch so that this adjustment may be verified). If there are two or more positive brushes abreast, try to arrange them so that the gaps between them are opposite the negative brushes so that the commutator will wear evenly. (It is well to shift the position of the brushes longitudinally from time to time.) Then, having verified these adjustments, remove all spanners and loose pieces of iron from the vicinity of the field-magnets. If there is any fear of the dynamo being started in the wrong direction, it is well that the brushes should be only lowered after starting. The current should always be turned off before the brushes are raised, otherwise a destructive spark will spoil the commutator.

It is necessary that carbon brushes should be very carefully fitted to the curvature of the commutator. One way of doing this is to paste round the commutator a strip of fine glass-paper and run the dynamo with the brushes in their normal position, until the ends are worn down to the right shape. Carbon brushes upon the whole give less trouble than copper brushes, as they do not wear the commutator so much nor do they spark so readily. A carbon brush should be free from the slightest suspicion of a crack or flaw, and a "glass-hard" corner should not be allowed to come in contact with the commutator.

The brushes being adjusted and lubricators filled, see that the connexions are right, and the terminals tightly screwed down. Bring

the machine up to speed slowly, keeping a sharp look-out for anything that may be wrong, and be ready to slow down at any instant. Do not raise a brush without having turned off the current unless there are two or more brushes side by side. If the machine is shunt-wound it will at once excite itself, though the main switch is still open. If the dynamo is for supplying glow-lamps, do not on any account turn on the main switch until you see whether the machine is giving the right volts, or you may ruin all your lamps. For if the speed is too high, the volts may be too high. A pilot lamp or a voltmeter will tell you if all is right. Then, before you turn on the main switch, observe the brushes to see if there is any sparking. If there is any sign of sparks, rock the brushes forward or backward till a sparkless place is found. Not until then should the main switch be turned and the lamps lit.

Daily Attention.—It is of the utmost importance to keep a dynamo scrupulously clean. A cotton rag should be used in preference to *waste*, as the latter leaves loose ends sticking to parts where it is objectionable. An air-blast is used by the Westinghouse Co. for getting rid of dust. Besides daily lubrication, attention must be given to the brushes to see if they require to be fed forward or trimmed. The commutator should not be oiled, but only wiped with a clean oily rag or a piece of cotton cloth (*not* waste) smeared with vaseline. (This reservation does not apply to arc-light dynamos with special commutators with wide air-gaps, which may be oiled freely.) Do not let the oil creep on parts that do not require it. Oil is apt to spoil the insulating materials by rotting the varnish, and affording a lodgment for dirt and for the fine copper dust that flies from the brushes. Also, if oil gets to the commutator it will char under the brushes, forming a carbonaceous film between the commutator bars, inviting a short-circuit. This fault is less likely to occur when mica-insulation is used than when asbestos or paper is employed. It has been observed that the brushes wear and heat unequally: the positive brush wearing faster than the negative. But this is unimportant. If there is solder on the brushes, care should be taken that the soldered part should never be used for contact on the commutator; it will set up flashing sparks.

If the dynamo is driven from heavy shafting, so that there is no risk of turning backwards at starting or stopping, then the brushes may always be left down on the commutator. Many dynamos will spark at full load unless the brushes are rocked forward beyond the point that gave sparkless running on open circuit. Sparkless running is a vital matter if the commutator is to last long. The attendant

cannot be too strongly impressed with the necessity of proper care on this matter. A well-designed modern dynamo, if properly attended to, will soon acquire a beautiful dark-polished surface on its commutator. But the commutator, even of a good machine, may be ruined in a few hours by careless or ignorant handling. If the brushes press too heavily it will become scored or ploughed up. If they press too lightly, or if there is vibration that causes them to jump, or if they are allowed to spark, the commutator will be worn away in patches at the edges of some of the bars, and lose its cylindricity of outline. The only remedy in this case is to carefully turn it or file it down true; this should occur very rarely.

In central stations, and in all cases where reliability of supply is imperative, the insulation should be tested throughout the machine every day. If the insulation resistance of any part has seriously fallen (even though it may still seem sufficiently great) the machine should not be started until the cause has been ascertained and removed. A daily insulation test gives very good indication of the dryness and cleanliness of the machine.

Diseases of Dynamos.[1]

At least four-fifths of the mishaps and break-downs that occur with dynamos arise from causes more strictly within the province of the engineer than in that of the electrician. On the other hand, many of the mechanical faults that develop themselves in the machine might have been avoided had the engineer been possessed of a better knowledge of the electric and magnetic conditions which obtain in the running of the machine. It is not often nowadays that armatures fly to pieces. That disaster has seldom occurred since good engineers took in hand the construction of dynamos. The points which it is difficult for the ordinary engineer to grasp are the mechanical stresses on the copper conductors due to the magnetic field, and the necessity throughout of preserving proper insulation. All insulation being mechanically bad, he is apt, in attempting to give mechanical strength, to use the insulating

[1] See paper by the author in *Electrician*, xx. 82, 1887; see also articles in *Electrotechnische Zeitschrift*, xi. 186, 1890; *Electrical World*, xiv. 99, 184, and xviii. 383, 1891; Crocker and Wheeler, *Practical Management of Dynamos and Motors* (Van Nostrand, New York); Lummis-Paterson, *Management of Dynamos* (Crosby Lockwood and Son, London); Parkhurst, "Diseases of Dynamos" *Trans. Amer. Inst. Elec. Eng.*, 1894.

materials in some way that vitiates their adequacy. For want of full electrical information he may apply the insulation in an erroneous manner and produce a dynamo which will break down under the severe conditions of actual work.

Burning-out of Armatures.—Single coils of an armature sometimes get heated to redness and burn the insulation. Sometimes a whole armature will become overheated, producing a general charring. The latter case happens more often to the armatures of motors than to those of dynamos. For if any excessive current is drawn by accident from a dynamo, the torque on the armature will generally become so great as to throw off the belt or pull up the engine. Whereas, with a motor, if the armature is jammed so that it cannot turn, an enormous current will continue to flow through it if the supply be not cut off.

Short-circuits in Armatures.—A short-circuit in the armature is usually first brought to notice by the smell of burning varnish. The machine should be shut down at once, and the armature felt all over with the hand. The short-circuited windings can generally be detected by their high temperature, even if the varnish is not visibly frizzled. If the greater part of the armature is short-circuited the fault is not so easily located by the rise in temperature. If an independent source of current is available a very good plan is to pass a strong current between two opposite bars of the commutator, and compare the drop in potential between the different pairs of bars. An intelligent application of Ohm's law will generally lead to the discovery of the fault or faults. For instance, we know that if the armature is perfectly sound the fall in potential on each side of the leading-in point will be the same, so that a galvanometer whose terminals are attached to commutator bars at equal distances on each side of the leading-in point will show little or no deflexion. As one passes from bar to bar the occurrence of a great deflexion will immediately point to a want of symmetry at that point. The cases that might arise are so numerous that it would be useless to attempt an exposition of all of them. The experimenter must trust to his previous electrical training and the application of common sense. Where there are faults to the ironwork of the armature a current may be passed from one of the commutator bars to the ironwork, and a similar investigation made of the drop in potential between different bars. Another method is to connect all the bars of the commutator together by winding wire round it and then passing a current from this wire to the ironwork. The armature will become magnetized, the poles being in the vicinity of the faults.

A short-circuit between an imperfectly insulated wire and the iron core beneath it is a fruitful source of trouble. Not that any *one* such contact can of itself produce any effect: but that if there is one such contact, then, if a fault occurs anywhere in the lamp circuit, there will at once be developed a serious leak through earth. Also the risk of shock to persons casually touching any part of the circuit is greater if there is any single fault in the dynamo. Some firms—chiefly American[1]—prescribe that the dynamo-frame itself should be insulated from the ground. The author's experience leads him to prescribe that the framework of the dynamo should, on the contrary, be carefully connected to earth. If this is done, the risk of accident to attendants—which is considerable in the case of high-voltage machines insulated from their bed—is reduced to a minimum. A contact between an armature conductor and the iron core may occur because of the iron laminæ becoming loose and wearing through the layers of insulation. If the insulation is not waterproof and has got wet, it may break down when the machine is run. Sometimes armatures are destroyed by the burning of the insulation, by the overheating, not of the conductors, but of the iron core. In such cases the core has not been properly laminated. The burning of binding wires, which occasionally occurs, is due to want of compliance with the sufficient and necessary electrical conditions.

Being pieces of running machinery, dynamos are liable, as all engines are, to heating of bearings, if proper attention is not paid to lubrication and to the avoidance of needless dirt.

Fracture of Connexions.—This most annoying fault—the fracture of the connecting pieces which lead down from the armature conductors to the bars of the commutator—appears to be partly mechanical and partly electrical. These connecting pieces pass through a partial magnetic field, and they carry at times strong currents, which are reversed twice in each revolution. Hence they are each racked by lateral forces as they rotate, and this incessantly repeated breaks them off at last. The cure is either to make them mechanically very strong, or of stranded material, or to arrange that they shall lie outside the waste field.

Disconnexions in Armature.—Sometimes a disconnexion occurs where the armature conductors or windings are coupled up or connected down to the commutator. The evidence of this is (i.) a

[1] The lightning-arresters used on many dynamos in the States are themselves a source of mishaps. If the dynamo-frame is properly earthed there is no need of a lightning-arrester on the dynamo. Efficient lightning-arresters should be fixed outside the dynamo-house where the overhead circuit enters it.

sparking that cannot be stopped by rocking the brushes forward or backward, and (ii.) one or more of the bars of the commutator appearing as if burned at the edge. One way[1] of finding the location of such a fault is to run the dynamo very slowly on short-circuit. Then after a few minutes' run stop the machine and see if any of the joints of the connectors are hot; this will indicate a partial disconnexion. If any entire coil is found to be hot, that is evidence not of a disconnexion, but of a short-circuit. Any disconnected coil in an armature is very easily found by the fall in potential method mentioned above. If the fault cannot be remedied at once, and it is necessary to run the machine, the bar belonging to the faulty coil may be connected to the succeeding bar by a blob of solder to stop the excessive sparking and preserve the continuity of the armature.

Flats in the Commutator.—Occasionally one of the commutator segments will become burned away or worn down to a lower level than the rest, or two adjacent bars may be similarly affected, causing a flat part on the cylindrical surface. Various suggestions have been offered to explain the origin of flats. If one of the bars was of unusually soft copper it might wear away faster; but the occurrence is unlikely. A partial disconnexion in the armature at the part connected to the particular bar of the commutator will give rise to a spark here at every half-revolution, so biting away this bar. Flats have been noticed also to spread along the bar from a flaw at one spot.

Another undoubted cause of flats is a mechanically weak or defective means of driving. If an armature, attached by a three-legged spider, is mounted on a weak shaft that bends, it is possible that periodic vibrations may occur which will cause the brushes to jump and set up sparks at definite points around the commutator. With well-constructed armatures, well-balanced and running without vibration, there is little fear of flats if the pressure of the brushes is sufficient. Whenever a bar of the commutator shows signs of burning along its edge, steps should at once be taken to prevent the development of a flat. A fine file should be applied to smooth the surface of the commutator in the neighbourhood of the threatened spot. Or, if need be, the commutator should be very slightly turned

[1] Another way, applicable only to drum armatures, is due to Loomis (*Electrical Engineer*, New York, December 1891), and consists in holding the armature by hand and slowly turning it round against the torque while supplied with a current from some external source. If a position is found where it is easier to turn, it is clear that in this position the disconnexion stops part of the current, so that the fault can at once be found by tracing the connectors which run from those bars of the commutator which are at the brushes in this position.

down. A narrow tool should be used for this purpose, so as not to drag the copper, and the surface should be polished with very fine glass paper and examined to see that at no spot has the thin strip of mica been bridged over by a burr at the edge of any of the bars.

Faults in Field-magnet Coils.—Sometimes faults occur in field-magnet coils. These may be of two kinds—disconnexions or short-circuits. When there is a disconnexion the machine will probably refuse to excite itself. To make sure, the suspected coil should be disconnected at the ends and tested. A cell of Leclanché battery and a simple detector galvanometer, or, failing this, a common electric bell, will suffice to prove whether the wire is continuous. If the frames on which the coils are wound are loose, the resulting vibration may cause the leading-out ends of the wires to snap, perhaps at some point below the surface which can only be reached by unwinding the coil. A short-circuit between any two of the windings will have the effect of keeping the short-circuited part cool whilst the rest of the coils are hot. In a shunt coil, short-circuiting some of the windings causes the rest to overheat dangerously. A short-circuit may arise between the frames or cores and the coils, and may be also tested for by electric bell or detector as above. If there is a single contact fault of this sort between coils and ironwork in the field-magnet, then a single fault at any other point—armature, commutator, brushes, terminals or circuit—may work dire disaster.

Dynamo fails to excite.—If a dynamo fails to excite, the first thing to do is to thoroughly overhaul all the connexions, particular attention being paid to the direction in which the current should circulate round the field-magnet coils: see that the brushes are in their proper position and are making good contact, and that the external circuit is open if the machine is shunt-wound, and closed if series-wound. If the dynamo still refuses to excite, lift the brushes and excite the field from some independent source, care being taken to give it the right polarity having regard to the direction of rotation and the manner in which it is connected up. In doing this it will be seen whether there is any break in field-circuit.

Faults of Alternators.—Alternators are liable to faults of special kinds. Sometimes they show a regular pulsating flicker, timed exactly to the revolutions of the armature. This can only be due to some double inequality. If one pair of poles of the field-magnet is weaker than the rest, and one of the armature coils is defective, then when these come together in position once in each revolution the current may show a momentary drop. Alternators are usually made for high voltage, and are therefore liable to faults of insulation that

might not occur in low-voltage machines. If the two collecting rings are side by side on the shaft, a spark—or rather arc—may spring over from one to the other unless a high projecting washer of ebonite is interposed. The field-magnet is necessarily brought into proximity with conductors differing greatly in potential, and great care is required to prevent these being short-circuited by arcs between them and the pole-pieces. The peculiar racking action of the alternating current on the armature coils (see p. 572) is responsible for many failures in this class of machine.

Vibration and Noise.—Excessive vibration can only be due to want of proper balance in the rotating part. Vibration of a kind that may, nevertheless, be disastrous to the dynamo, racking its conductors, pounding its insulation to dust and causing the brushes to jump and spark, may be occasioned, even in a well-balanced machine, if it is not firmly secured to a proper foundation. Continuous-current machines should run practically silently; the belt will make far more noise than any part of the dynamo. Alternators do not usually run silently, for the coils of all disk armatures churn the air between the poles. If the iron cores of the armature part are subjected to too severe a cycle of magnetization they will emit a loud humming sound, which cannot be cured except by using the machine at a lower degree of excitation, being a defect of design. Once the author came across a remarkable case of an alternator which emitted a sustained howling sound of piercing loudness. The cause in this case was the accidental coincidence between the number of alternations and the natural vibration period of some of the solid iron parts. It was cured by re-fitting the iron parts so as to alter the fulcrum from which the parts could vibrate.

APPENDIX A.

ON WIRES.

On p. 369 were given some data respecting the sizes of wire found suitable in practice for winding dynamos for different currents. Other data are to be found in the detailed descriptions of various machines in other parts of this book. The question of heating in relation to current-carrying capacity was also treated in Chapter XVI. in some detail.

A few further points may be added here, founded upon information given by wire-makers, and in particular by the London Electric Wire Company.

The usual insulation for round wires of a greater diameter than No. 16 S.W.G. is a double cotton covering which increases the diameter by amounts varying from 10 to 20 mils, but which usually averages 14 mils. For smaller sizes, from No. 18 to No. 22 S.W.G , the usual double cotton covering is an addition of 12 mils. Square wire is usually double-cotton covered to 20 mils additional, or is sometimes braided. Laminated square wire—i. e. made of a number of narrow strips, is usually braided to about an equal amount. Since stranded wires came in for armature winding, several modes of insulating have been adopted, and one maker employs a cable of 37 wires, each No. 15 S.W.G., each single cotton covered; the whole being double-cotton covered to 16 mils additional, or braided to 20 mils. For transformer windings at high voltage a frequent practice is to wind a much thicker cotton insulation for subsequent immersion in oil. For example, a No. 23 S.W.G. wire is cotton covered to 40 mils additional, thus nearly doubling the weight of the wire.

Annexed is a table useful in magnet winding, showing the probable heating, and greatest permissible depth of winding at various amperages. It is to be remembered that 2000 amperes per sq. in. is a common density of current for field-magnets; the density in armatures runs to 3000 or more; whilst in transformers the amperage is as low as 600 or even 450 (see p. 371.)

WIRE GAUGE AND AMPERAGE TABLE.

Dimensions.				Permissible Amperage, Probable Heating, and Permissible Depth.											
S. W. G.	Diam.	Section (sq. inch).	Turns to 1 linear inch.	1000 Amperes to sq. inch.			2000 Amperes to sq. inch.			3000 Amperes to sq. inch.			4000 Amperes to sq. inch.		
				A	F	D	A	F	D	A	F	D	A	F	D
22	·028	·00062	23·81	·616	0·91	4·5	1·23	3·63	1·13	1·85	8·16	·50	2·46	14·5	·28
20	·036	·0010	20·00	1·018	1·29	3·9	2·036	5·17	·97	3·05	11·6	·43	4·07	20·7	·24
19	·040	·0012	18·52	1·26	1·53	3·6	2·52	6·02	·92	3·78	13·8	·41	5·04	24·5	·23
18	·048	·0018	16·13	1·81	1·83	3·3	3·62	7·32	·83	5·43	16·4	·37	7·24	29·3	·21
17	·056	·0024	14·28	2·4	2·14	3·2	4·8	8·56	·79	7·2	19·3	·35	9·6	34·2	·19
16	·064	·0032	12·83	3·2	2·57	3·0	6·4	10·28	·74	9·6	23·1	·33	12·8	41·1	·18
15	·072	·0040	11·63	4·0	2·90	2·9	8·0	11·6	·72	12·0	26·2	·32	16·0	46·4	·17
14	·080	·0050	10·64	5·0	3·33	2·8	10·0	13·3	·70	15·0	30·0	·31	20·0	53·3	·17
13	·092	·0060	9·44	6·6	4·29	2·7	13·2	17·2	·67	19·8	38·7	·30	26·4	68·8	·16
12	·104	·0085	8·48	8·5	4·52	2·6	17·0	18·1	·65	25·5	40·7	·29	34·0	72·3	·16
11	·116	·0105	7·69	10·5	5·07	2·5	21·0	20·3	·63	31·5	45·7	·28	42·0	81·2	·16
10	·128	·0128	7·04	12·8	5·67	2·4	25·6	22·7	·61	38·4	51·0	·27	51·2	90·7	·15
9	·144	·0163	6·33	16·3	6·50	2·4	32·6	26·8	·60	48·9	58·5	·27	65·2	104·5	·15
8	·160	·0201	5·74	20·1	7·28	2·3	40·2	29·1	·59	60·3	65·5	·26	80·4	116·4	·15
7	·176	·0243	5·26	24·3	8·06	2·3	48·6	32·2	·58	72·9	72·6	·26	97·2	129·0	·15

Stranded.															
7/22	·084	·0043	9·62	4·3	2·59	4·0	8·6	10·3	·99	12·9	23·3	·44	17·2	41·4	·25
7/20	·108	·0072	7·81	7·13	3·45	3·7	14·3	13·8	·92	21·4	31·2	·48	28·5	55·2	·23
7/18	·144	·0128	6·09	12·7	4·94	3·4	25·4	19·7	·83	38·1	44·5	·39	50·8	79·0	·21
7/16	·192	·0229	5·10	22·9	7·37	3·2	45·8	29·5	·79	68·7	66·3	·35	91·6	117·9	·20
7/15	·216	·0289	4·27	28·9	7·79	3·1	57·8	31·2	·78	86·7	70·1	·34	115·6	124·6	·20
7/14	·240	·0356	3·87	35·6	8·72	2·7	71·2	34·8	·76	106·8	78·4	·34	142·4	139·5	·19
7/13	·276	·0462	3·38	46·2	9·91	2·0	92·4	39·6	·74	138·6	89·2	·33	184·8	158·5	·19
7/12	·312	·0595	3·01	59·5	11·4	1·9	179·0	45·5	·72	178·5	102·5	·32	238·0	182·2	·18

Figures in columns marked A signify number of amperes that the wire carries.

Figures in columns marked F signify number of degrees (Fahrenheit) that the coil will warm up if there is only one layer of wire; they are calculated by Esson's modification of Forbes' rule:—

Rise in temperature (Fahrenheit degrees) = 100 × number of watts lost per sq. inch.
= 69 × sectional area × number of turns to 1 inch (at 1000 amperes per sq. inch).

Figures in column marked D are the depths in inches to which wire may be wound if 1 watt be lost by each square inch of radiating surface, the outside radiating surface of the bobbin only being considered.

Rule for calculating a 7-strand cable:—Diameter of cable = 1·134 × diameter of equivalent round wire.

Figures under heading "Turns to 1 linear inch" are calculated for cotton-covered wires of average thicknesses of coverings used for the different gauges, viz.: 14 mils additional diameter on round wires (from No. 22), and 20 mils on stranded or square wire.

Resistance (ohms) of coil of copper wire, occupying v cubic inches of coil-space, and of which the gauge is d mils uncovered, and D mils covered, may be approximately calculated by the rule:—

$$\text{ohms} = 960700 \frac{v}{D^2 d^2}$$

The following rules which have been given by Kapp, are useful for preliminary calculations about depth of winding and weight of wire. If l is the length of wire in inches, D the depth of winding-space in inches, X the ampere-turns of excitation, P the perimeter in inches, and W the weight of the coil in pounds, we have

$$X = a\,l\sqrt{D}; \qquad [i.]$$

where a is a coefficient which depends on the gauge of wire and thickness of its insulation. Also

$$W = \beta \frac{P}{l} \sqrt{\frac{X}{1000}}; \qquad [ii.]$$

where β is a second coefficient varying with the gauge of wire.

These two formulæ are applicable to the case where a temperature-limit being imposed we allow $2\frac{1}{2}$ square inches per watt. If no such limit is imposed and a given expenditure of energy is assumed, it is more convenient to replace them by the following formulæ :—

$$X = \gamma \sqrt{W\,l\,D} \div P, \qquad [iii.]$$

$$W = \delta \frac{P^2 X}{1{,}000{,}000\ D}. \qquad [iv.]$$

The four numerical coefficients then have the following values:—

Diam. of Bare Wire in mils.	S.W.G.	α.	β.	γ.	δ.
40	19	522	0·495	820	0·195
120	$10\frac{1}{2}$	542	0·520	850	0·205
200	$5\frac{1}{2}$	570	0·615	900	0·246

Another useful rule for calculating wiring is that a copper wire 1 foot long, and 1 square mil (i. e. one-millionth of a square inch) in cross-section has a resistance of 9·4 ohms, at a temperature of 60° Centig.

Yet another set of rules is convenient when calculating the size of a round wire or rectangular strip which will carry any given current with a prescribed drop of voltage.

Let C be the number of amperes the wire is to carry, v the drop of volts permitted, l the total length in feet, λ the mean length per turn in feet, S the number of turns in the coil, r the resistance in ohms, W the weight in pounds, A the sectional area in square inches

(if rectangular), and d the diameter in inches (if round). Obviously $r = v \div C$.

Then we have the following rules, in which the constants are chosen to suit a temperature of about 40° (Centigrade).

ROUND WIRE.	RECTANGULAR STRIP.
$d = 3{\cdot}43\sqrt{\frac{C\,S\,\lambda}{v}} \div 10^3$	$A = 9{\cdot}2\,\frac{C\,S\,\lambda}{v} \div 10^6$
$r = 11{\cdot}75\,\frac{S\,\lambda}{d^2} \div 10^6$	$r = 9{\cdot}2\,\frac{S\,\lambda}{A} \div 10^6$
$W = 3{\cdot}02\,d^2\,S\,\lambda$	$W = 3{\cdot}85\,A\,S\,\lambda$

APPENDIX B.

NUMERICAL STATISTICS ON ELECTRO-METALLURGY.

The following data are useful for reference in deciding what the electrical capacity of a dynamo must be in order that it may deposit metal in any desired quantity :—

Copper.

Current	1	ampere	deposits	0·000326	grammes	per second.
,,	1	,,	,,	0·01957	,,	per minute.
,,	1	,,	,,	1·1739	,,	per hour.
,,	851·8	,,	,,	1	kilogramme	per hour.
,,	386·4	,,	,,	1	pound	per hour.

To deposit 100 lbs. of copper in a working day of 10 hours will require 3864 amperes of current flowing all the time ; or, if conducted in ten baths in series with one another, will require 386·4 amperes, but in that case the dynamo will require to be of an electromotive-force ten times as great as for one single large bath. If electrolysis of the crude copper solution is carried on with carbon anodes, there will be required about 1·2 volts for each bath in series, or, at most, 15 volts for the ten baths.

Silver.

Current of	1	ampere	deposits	4·025	grammes	per hour.
,, ,,	112·7	,,	,,	1	pound	per hour.

Gold.

Current of	1	ampere deposits	2·441	grammes	per hour.
„ „	185·8	„ „	1	pound	per hour.

Nickel.

Current of	1	ampere deposits	1·099	grammes	per hour.
„ „	412·8	„ „	1	pound	per hour.

The following statistics as to the various pressures and currents required in various processes of electro-deposition are useful for reference:—

PRESSURE AT TERMINALS REQUIRED FOR DIFFERENT KINDS OF BATHS.

	Volts.
Copper (acid baths)	0·5 to 1·5
„ (cyanide bath)	3 „ 5
Silver	0·5 „ 1
Gold	0·5 „ 4
Brass	3 „ 5
Iron (steel facing)	1 „ 1·3
Nickel on iron, steel, copper, with nickel anode, strike deposit with 5 volts, diminishing to	1·5 „ 2
Nickel on iron, steel, copper, with carbon anode	2 „ 4
Nickel on zinc	4 „ 7
Platinum	5 „ 6

CURRENT DENSITY FOR PROPER DEPOSIT.

	Amperes per 100 sq. inch.
Copper Typing—	
Best quality tough deposit	1·5 to 4
Good and tough (for clichés)	4 „ 10
Good solid deposit	10 „ 25
Solid deposit, sandy at edges	25 „ 40
Sandy and granular deposit	50 „ 100
Copper (cyanide bath)	2 to 3
Zinc (for refining)	2 „ 3
Silver	1 „ 3
Gold	0·5 „ 1
Brass	3 „ 3·5
Iron (steel-facing)	0·5 „ 1·5
Nickel at first deposit 9 to 10 amperes per 100 square inches, diminishing afterwards to	1 „ 2

APPENDIX C.

FORMS OF SPECIFICATION.

The following hints for drawing up Specifications for tenders are intended to cover the points really necessary for securing first-class machines without too closely tying down the details.

SPECIFICATION OF CONTINUOUS-CURRENT DYNAMOS.

1. All the [four] dynamos are to be of the same [bipolar] [shunt-wound] continuous-current type with ventilated [drum] armatures. All dynamos of the same size are to have corresponding parts interchangeable. Each dynamo is to be arranged to stand upon the same bed-plate as its engine, and to be driven direct from its crank-shaft.

2. [Two] of the dynamos to be of [200] kilowatts normal output—viz. to give out normally [800] amperes at [250] volts, running at [350] revolutions per minute. The other [two] dynamos are to be of [50] kilowatts normal output—viz. to give out normally [400] amperes at [125] volts, at [450] revolutions per minute.

3. [Two] spare armatures must be supplied, one of each size.

4. The dynamos must be so constructed that when run at an absolutely constant speed, the terminal voltage, when the excitation is unchanged, shall not drop more than [5] per cent. from no-load to full load: and the shunt windings must be such that when all regulating resistance is cut out, the terminal volts at no load shall be [270] volts in the larger machines, [135] volts in the smaller machines, at normal speed.

5. The dynamos are to carry their full loads without undue heating, either from mechanical or electrical causes. The excess of temperature of any part of the armature or field-magnet above the surrounding air is not to exceed 40° Centigrade when measured on bare copper or bare iron, after a continuous run of six hours with the maximum specified output. Each armature must be so constructed that a thermometer can readily be inserted in it for ascertaining the temperature.

6. A regulating resistance is to be provided for the shunt circuit of each dynamo. This resistance is to be of either platinoid or German silver wire; and its regulator switch must have not less than

[25] contacts. Allowance must be made in the tender for the necessary connecting wires, the switches being at a distance of [16] feet each from its dynamo, and the resistances in the place provided in the engine-room at an average distance of about [65] feet from the switches. All leads from dynamos to regulator-switches, and from regulator-switches to resistances must be carried in well insulated conduits or casings. The regulating resistances are to be such that the currents they carry shall in no case exceed [1200] amperes per square inch, or that they shall not become hot enough to melt ordinary solder when carrying a current 50 per cent. in excess of their normal maximum. They shall be enclosed in suitable fire-proof cases affording ample ventilation.

Each regulating resistance must also be such that when the dynamo is running at its full normal speed, but without load, the terminal voltage can be lowered from the normal value of [125] volts to [95] volts in the case of the smaller machines, or from [250] volts to [190] volts in the case of the larger machines; and must also be such as to permit the terminal voltage of the smaller machines to be raised to [135] volts, and that of the larger to [270] volts.

7. The dynamos must be capable of standing a temporary overload of 50 per cent. without injurious sparking at the commutator.

8. The armature winding must be so designed with respect to the mode of connecting down to the commutator that the brushes in their normal position shall be readily accessible. The rocker must be provided with a fine adjustment, and the brush-holders must be provided with hold-off catches, as well as with devices for the regular feeding of the brushes, allowing of the utmost economy in the use of short lengths of brush. The larger machines will have [3] brushes in each range, the smaller [2].

9. The whole of the circuits are to be throughout of copper of a conductivity not less than 99 per cent. of Matthiessen's standard for pure copper; the insulating materials used must be of the best, and be such that they will stand the application of an alternating pressure of [2000] volts between the copper and the iron parts. And when warm after a continuous run of not less than six hours, the insulation resistance between iron and copper shall not be less than [20] megohms in either the armature or the field-magnet.

10. Drawings for approval showing in sufficient detail the proposed construction of the dynamos are to be submitted with the tender. The drawings should show the mechanical construction of the armature, the mode of driving and insulation of the armature conductors, the outer bearing, and the proposed arrangements of brush-

holders, terminals and lubricators. They should also show the mode of carrying the magnets upon the bed-plate of the combined plant.

11. Each dynamo when complete is to be tested, either at the contractor's works, or at the station with its own engine. The tests will include a six-hours' continuous run under maximum load; and the conditions of this specification as to output, regulation, temperature and efficiency will be rigidiy enforced.

In case the same contractor supplies both dynamos and engines, the following clauses may be added :—

12. The combined efficiency of the dynamo and steam engine when under test must at least reach the following limits: The ratio of the electrical power as measured by standard amperemeter and standard voltmeter at the terminals of the dynamo, to the power developed by the engine as measured by an indicator of approved pattern shall be [86] per cent. for the [two] larger machines, and [82] per cent. for the [two] smaller machines.

13. The fact that the dynamos may have satisfactorily passed the tests, if made at the contractor's shops, shall in no way lessen the responsibility of the contractor for obtaining the like results after the machinery shall have been permanently erected in the station. The costs of these tests are to be borne by the contractor, and covered by this tender; and the tests are to be carried out to the satisfaction and in the presence of the engineer.

Specification of Alternators.

1. The Alternators are to be of the [single-phase] [separately-excited] type with [stationary] armatures and [revolving multipolar] field-magnets, direct-driven. They are to be of the same size, and to have corresponding parts strictly interchangeable. Each alternator is to be designed to stand upon the same bed-plate as its engine, and to be directly coupled to its crank shaft.

2. [Four] alternators are required. They are to be of [105] kilowatts normal output, viz.: to give out normally [50] amperes at [2100] volts, running at [400] revolutions per minute.

3. The alternators are to work with a frequency of [60] periods per second; and the combined plants must be capable of running continuously in parallel at all loads.

4. The field-magnets of the alternators must be so designed that the total energy absorbed in exciting the field-magnets of any one alternator shall not exceed [2] kilowatts at full load: and they must become fully excited when supplied at [200] volts.

5. Regulating resistances must be provided, one for each alternator, in the exciting circuits. The regulating resistance of the alternators must have a sufficient range to operate if exciter circuit varies from [200] and [250] volts.

6. Special care must be taken in the design and construction of the [revolving] field-magnets that they shall be properly balanced, that under no circumstances of using shall the exciting coils shift in their places; and that all chance of either a short-circuit or a disconnexion shall be made impossible. Duplicate brushes and brush-holders of substantial construction are to be furnished to each slip-ring in the exciting circuit; and the insulation of the exciting circuit in protected conduits must be very substantial.

7. The armature must be of such construction that while of great mechanical strength it admits of individual coils or groups of coils being readily replaced; whilst the armature as a whole must be accessible for daily cleaning and inspection. The terminals of the armature circuit must be specially well insulated, and protected against risk of contacts.

8. The total drop in volts, at full load, when running on an ordinary load of lamps or on a plain non-inductive resistance, must not exceed [200] volts when the excitation is kept constant.

9. The alternators are to carry their full load without undue heating either from mechanical or electrical causes. The excess of temperature above that of the surrounding air must not, in any part of the armature or field-magnet, exceed [40] deg. Centig. after a continuous run of six hours under the maximum normal load.

10. The whole of the circuits are to be throughout of copper, having a conductivity of not less than 99 per cent. of Matthiessen's standard: and the insulation shall be the best that can be procured. The insulation of the armature and of the field-magnet as between the copper conductors and the core or frame shall be such as to be capable of mechanically resisting being pierced by an electric spark at 4000 alternating volts.

11. One spare set of armature coils or sections is to be provided by the contractor.

12. Drawings for approval showing in sufficient detail the proposed construction of the alternators are to be submitted with the tender. The drawings should show the magnetic and mechanical construction both of field-magnet and of armature; the mode proposed for securing adequate insulation of armature conductors; the proposed arrangements of the exciting circuit, slip-rings, and contact brushes; the mode of insulating the high-pressure terminals; the

bearings and proposed system of lubrication; the coupling of the shafts.

13. Each alternator when completed is to be tested, either at the contractor's works, or at the station, with its own engine. The tests will include a six-hours' continuous run under maximum load, and the conditions of this specification as to output, regulation, insulation, temperature, parallel working and efficiency will be rigidly enforced.

In case the same contractor supplies the engines as well as the alternators, the following clauses may be added :—

14. The combined efficiency of the alternator and engine when under test must at least reach the following limits: the ratio of the electrical power as measured by standard wattmeter at the terminals of the alternator, when working on a non-inductive load, to the power developed by the engine as measured by an indicator of approved pattern, shall be [82] per cent. at full load, and shall be [75] per cent. at one-quarter load. The certificate of [the Board of Trade] shall be deemed a sufficient guarantee of the correctness of the readings of the wattmeter.

15. The fact that the alternators may have satisfactorily passed the tests, if made at the contractor's shops, shall in no way lessen the responsibility of the contractor for obtaining the like results after the machinery shall have been permanently erected in the station. The costs of these tests are to be borne by the contractor, and covered by this tender; and the tests are to be carried out to the satisfaction and in the presence of the engineer.

Specification of Transformer.

1. The number of transformers required is [six]. They are all to be of the [double-limb upright] type, having each an output of [20] kilowatts. The ratio of transformation is from [2100] to [105] volts; and the normal current in the secondary circuit is [190] amperes; but each transformer must be capable of working at a temporary maximum load of [220] amperes without injury, for a time not exceeding twenty minutes. The transformers to be wound for a frequency of [60] periods per second.

2. The cores are to be constructed of the best Swedish charcoal iron plates not exceeding [20 mils] in thickness, carefully annealed, and coated with tough insulating varnish. The core-plates when built up are to be interleaved at the joints so as to form a complete

magnetic circuit of uniform section, and held tightly together by insulated bolts. The assembled cores to be covered with tape, varnished with shellac varnish, and well-baked before the coils are placed upon them.

3. The primary and secondary coils are to be of copper, having a conductivity of not less than 99 per cent. of Matthiessen's standard, and are to be double-cotton covered to a depth of [20 mils] and wound on separate concentric cylinders of ozokerited compressed paper. A thin layer of insulating material to be placed during winding between every layer of wire, and in addition a sheet of ebonite at least [40 mils] thick to be interposed between the primary and secondary coils. The winding of the two secondary coils to be such that both of the ends that are to go to the two secondary terminals shall be the ends of outside layers. The whole of the insulation and materials used must be of the best quality.

4. The resistances and current densities in the copper, and the flux-density in the iron, must be such that the transformer shall be capable of working for any length of time at full normal load without overheating in any part, and on a run of six consecutive hours at full normal load shall not rise more than [50] deg. Centig. above the temperature of the surrounding air. Nor must the drop in the voltage at the terminals of the secondary coil, from no load to full load, when the primary pressure is maintained constant at the primary terminals, exceed [1½] volts when working on a non-inductive load.

5. The coil ends are to be brought to well-insulated terminal plates inside the case, and suitable terminal screws are to be provided for attachment of high and low-voltage conductors. The case is to be of cast iron, closed by a suitable cast-iron cover rendered air-tight and water-tight by a rubber packing. Metal glands bushed with ebonite are to be provided for both the low and the high-pressure conductors.

6. Drawings for approval showing in sufficient detail the general construction of the transformers, and in particular the modes of securing the transformer in its case and of leading out the conductors, are to be submitted with the tender.

7. Each transformer must have an insulation resistance between the primary and secondary windings of not less than 25 megohms; and before being tested at the works must be subjected between primary and secondary and between coils and core to an alternating pressure of at least 4500 volts. After delivery at the station each transformer is to be tested, the tests to include a six hours' continuous run at full normal load; and the conditions of this specifica-

tion as to output, ratio of transformation, regulation, temperature and efficiency will be rigidly enforced.

8. The efficiency of each transformer when under test, and when warm after a continuous run of six hours, must at least reach the following limits: the ratio of the electrical output of power as measured by certified wattmeter at the secondary terminals, when working on a non-inductive load, to the input of power as measured by certified wattmeter at the primary terminals, at normal pressure and frequency, shall be [97] per cent. at full load and [93] per cent. at one-quarter load. The certificate of [the Board of Trade] shall be deemed a sufficient guarantee of the correctness of the wattmeter used in these tests.

9. The fact that the transformers may have satisfactorily passed these tests before delivery shall in no way lessen the responsibility of the contractor for obtaining the like results after the transformers shall have been delivered at the station. The costs of these tests are to be borne by the contractor, and covered by this tender; and the tests are to be carried out to the satisfaction and in the presence of the engineer.

INDEX.

A

	PAGE
ACCUMULATOR charging, dynamos for ..	472
Achard, on motor efficiency ..	492
Activity of motor ..	492
Adams, W. G., on dynamo tests ..	763
Addition of alternating quantities ..	556
Adjustment of brushes ..	770
Admiralty specification as to temperature rise ..	375
Advantages of drum winding ..	303
Of high voltage ..	694, 732
Of open coil armatures ..	464
Air-blast for cleaning ..	771
For spark prevention ..	463
Air friction ..	106
Air-gap in magnetic circuit ..	128
Effect of increase of ..	384
Effect of widening ..	379
Alioth & Co.'s alternators ..	636
Allgemeine Elektricitäts Gesellschaft—Alternators ..	627
Continuous-alternating transformer ..	731
Inductor alternators ..	642
Motors ..	538
Regulator ..	745
"Alliance" machine ..	10
Alteneck, von Hefner—Disk dynamo ..	479
Drum-wound armature ..	15
Graphic construction of transmission ..	738
Alternate current—Principles of ..	547, 551
Analytical theory ..	573
Electro-magnets ..	566
Polyphase ..	555, 579, 628, 662
Of extra high frequency ..	570
Skin effect ..	578
Transformers ..	695
Transmission of energy by ..	736

PAGE
Alternate-current motors—Monophase 687
Polyphase 662
Retarded field 693
Series 693
Split-phase 689
Synchronous 647
Alternating-continuous transformers 728
Alternating and rotating vectors 690
Alternators 579
As motors 647
Armature winding of 580, 597
Asynchronous 606
Construction of 601
Coupling of 647
Excitation of 594
Faults of 776
For constant current 595, 640
For constant voltage 595
Fundamental formula of 46, 658
In parallel 659
Specification of 787
Torque of 571
Width of pole-faces, &c. 588
Aluminium, dynamos for reducing 412, 471
Amperage 340, 346, 371, 622, 779, 780
Ampère, on early dynamo 7
Ampère's rule as to direction of electromotive-force 22
Ampere-turns 117
Required on magnetic circuit 148
Calculation of 350, 356, 361, 364
Amperes, virtual 554
Amplitude of alternating quantity 550
Of magnetic cycle 136
Analogy between electric and magnetic circuit 119
André's motor 522
Angle of lag of current 556, 562
Of lead of current 566
Of lead of brushes 72, 85, 382, 448, 395, 514
Of polar span 74, 387, 588
Angular speed 101, 173, 367, 549, 675
Anti-friction bearings 333
Apparent resistance of armature 89
Apparent watts 567
Appold's improvement of Prony brake 754
Arago's rotations 66
Arc lighting—Alternators 595, 640

PAGE

Arc-lighting Dynamos 445
 Armature, winding of 301, 447
 Characteristic of 205
Armature—Balancing of 295, 331, 775
 Binding of 43, 106, 296
 Bar 296, 304
 Burning out of 773
 Closed coil 39
 Construction of 284, 580
 Coils of 243
 Coils wound on formers 301, 310
 Coils of alternator, breadth of 588
 Connecting up of 581, 585, 587, 590, 596
 Core of 41, 45, 90, 284, 286, 290, 367, 451, 583, 602
 Compensation 388, 391, 394
 Cooling surface of 375
 Definition of 3, 34
 Diameter of.. .. .. 342, 377
 Disk 43, 278, 442, 585
 Design of 341, 602
 Drum 15, 41, 76, 244, 255, 265, 302, 583
 Exploration of 63
 Faults of 773
 Gyrostatic action of 328
 Heating of 295, 369, 375, 773
 Insulation of 44, 294, 296, 452, 616, 623
 Iron in 593, 602
 Length of 342, 377, 386, 398
 Open coil 40, 447
 Pole 43, 584
 Practical construction of 284
 Reaction of 70, 380, 387, 478, 510, 596, 654
 Ring 40, 245, 258, 275, 300, 580
 Support of 327
 Torque of 96, 100, 102
 Ventilation of 164, 292, 295, 403, 616, 622
 Winding of.. .. .. .. 243, 289, 297, 342, 369, 452, 580
Arnold, on alternate-current motors 21
 On armature winding 21
 On homopolar induction 478
 On multipolar rings 278
Arnoux, on disk winding 280
 On widening of gap-space 380
Asynchronous generators 606
Asynchronous motors 662

PAGE

Atkinson Ll. B. (*see* also Goolden)
Homopolar dynamo 477
Mining motor 539
Pulsating motor 546
Auerbach, on theory of dynamo 20
Augmentor 718
Automatic regulators (*see* Regulators)
Auto-transformers 718
Auxiliary winding on armatures 394
Average electromotive-force 172, 555
Ayrton, W. E., on armature reaction 86
On size and output 110
On dynamo testing 763
On power transmission 492
Ayrton & Perry, on brake dynamometer 755
Constant-speed motors 18, 521, 522
Motor 532
On magnetic shunts 155
On sparkless commutation 515
On spurious resistance 89
On thickness of gap-space 398
On transmission of power 740
Periodic governor 521

B

BACK electromotive-force (*see* Counter electromotive-force)
Backward lead of brushes 87, 395, 396, 514
Baker, on self-excitation 12
Baking and drying armatures 300
Commutators 317
Balance method of measuring power 756
Balancing of armatures 295, 331, 775
Ball bearings 333
Bar armatures 298, 304, 402, 405, 480
Barlow's rotating wheel 17
Barr, Beeton and Taylor, on wave form 553
Barr, Burnie and Rodgers, on wave form 553
Bars of commutator (*see* Commutator)
Bast, De, on rotatory-field motors 21
Baumgardt, on compound winding 242
Bearings 332
Pressure on 327
Self-oiling 336
Bedell and Crehore, on graphic constructions for alternating
currents 552

PAGE
Bedell, on mutual induction 720
Bedell, Miller and Wagner, on finding form of wave 553
Bedell and Ryan, on synchronous motors 21, 651, 654
Bed-plates 152, 159, 337, 769
Bell, Louis, on compound winding 242
Belt-collectors 326
Bending stress on shaft 331, 775
Berlin central station dynamos 407
Berlin type of ring armatures 275, 302
Bifurcation of current 257
Binding-wires 43, 296
Blakesley, T. H., on alternating currents 552
On three-dynamometer method 568
Blakey-Emmott alternator curve 553
Blondel, on synchronism of alternators 21, 653
Bollman disk dynamo 479
Booster 726
Borel's motor 689
Bosanquet, on magnetomotive force 116
Bourbouze's motor 483
Brackett's method of measuring power 757
Bradley, C. S.—Arc-light dynamos 465
On polyphase work 665
Two-phase alternator 599
Two-phase motor 671
Brake for measuring power 754
Branched magnetic circuits 119, 150, 165
Breadth of brushes 313, 320
Breadth-coefficient 589, 592
Breguet, A., on theory of dynamo 4
Brett's self-exciting dynamo 9
Brotherhood's coupling 338
Brousson, on alternator's output 589
Brown, C. E. L.—Alternators 632
Arrangement of alternator coils 604
Cylindrical winding 310
Dynamos 415
Electro-metallurgical dynamos 413, 472
Four-pole dynamos 409
Flexible-band collector 326
Homopolar dynamo 477
Method of driving core-disks 292
Motors 410
Multipolar field 165, 397, 409
Pierced core-disks 99, 290, 628
Polyphase motors 673

PAGE

Brown, C. E. L.—
Three-phase alternator 627
Three-phase inductor alternator 646
Transformer 705
Brown, Boveri & Co. (*see* Brown, C. E. L.)
Brush—Arc-lighting dynamo 451
Commutator 454
Machine characteristic 205
Open-coil dynamo 16
Uses shunt and series coils 56
Electro-plating dynamo 470
Induction sheath 451
Regulator 746
Brush Electrical Engineering Co.—Alternators 619
Dynamos 417
Brush-holders 321
Insulation of 324
Brushes 32, 312, 318
Carbon 319, 770
Care of 770
Lead of 72, 76, 78, 85, 382, 395, 448, 514
Of arc-light dynamo 448, 454
Thickness of 320
Position of 514, 786
Burgin machine 285
Burning out of dynamos 773
Burstyn, on parallel running 766
Bushed pole 393

C

Cabanellas, on continuous-current transformation 727
On spurious resistance 90
On demagnetizing effect of eddy-currents 92
Calculations of dynamo 339, 345
Of efficiency 347
Of magnetic circuit 348, 350, 356, 361, 364
Caldwell's regulator 747
Capacity in circuit 564, 576
In mains 566
Carbon brushes 319, 320, 770
Cardew, Major, on dynamo testing 758
Voltmeter 554
Carhart, on Jacobi's law 500
Carpentier, on brake dynamometer 755
Cast iron, magnetic properties of 122

PAGE

Causes of sparking 79, 83, 381
Centrifugal governors 520
C.G.S. magnetic units 144
Characteristic curves 196
Of separately excited dynamo 185
Drooping 466, 766
External 202
Internal 210
Relation of, to winding 207
Of motors 502, 505
Choking coils 566
Choking coil, transformer as 698
Circuital distribution of vectors 115
Circuit—Electric 26
Magnetic 114
Circulation of power 758
Circumflux 383, 384
City and South London Railway plant 545
Clarke's dynamo 8, 479
Clausius, R., theory of dynamo 20, 190
Cleaning dynamo 771
Clerk Maxwell (*see* Maxwell)
Clock diagram 550, 591, 648, 652
Closed-coil armature 37, 39, 61
Magnetization of 71
Two paths through 60, 62
In arc-light dynamos 466
Coefficient of leakage 151
Of self-induction 560, 720
Of transformation 697, 720, 727
Coercive force 133
Coils—Of alternator 604
On transformers 704
Position of magnetizing 150
Collars on shaft 331
Collecting rings 312, 326, 385
Collector (*see* Commutator)
Combined plant 762
Commercial efficiency 347
Commutation—Diameter of 78
In motors 514
Commutator 32, 37, 40, 312
Bars 80, 313
Care of 770, 771
Distribution of potential on 66, 68
Exploration of 63

PAGE

Commutator—
- Flats in 775
- For rectifying 594
- Invented by Sturgeon 9
- Of Berlin dynamos 302, 407
- Of Brush dynamo 452
- Of open-coil dynamos 447
- Of Thomson-Houston machine 450
- Of tramway generator 434
- Outer portions of conductors as 275, 302, 407
- Sparking at (*and see* Sparking) 78

Commuting coils 438
Comparison of single and polyphase alternators 601
Compensated armatures 386, 388, 391, 394
Compound dynamos, coupling of 767
Compound winding 17, 55, 233, 522
- Calculation of 363
- Experimental determination of 366
- In arc-light dynamos 446
- In motor 522
- In alternators 595
- Slow in action 142

Compression, effect of, on magnetization 294
Concentration of field 393
Condenser, action of synchronous motor 654
Conductors—Drag on 96, 103
- Embedding of 99
- Kinds of, on armatures 299, 343
- Lamination of 343
- Moved in magnetic field 22
- Number of 168

Connecting up alternate-current armatures .. 581, 585, 587, 590, 596
Connectors 304
- Junction with commutator 318

Consequent poles 161
Constant-current 502, 508, 512
- Alternators for 595, 640
- Dynamos for 445
- Motors for 530
- Regulators for 744
- Transformers for 717

Constant electromotive-force 182
Constant speed 502, 511, 522, 529
Constant torque 502, 508, 749
Constant voltage 54, 505, 508, 511, 523
- Dynamos 54, 224

PAGE

Constant voltage—
Alternators 595
Regulators 744
Construction, practical, of armatures 342
Of alternators 601
Of commutators 315
Of motors 531, 673
Of transformers 700
Continuous-alternating transformers 728
Continuity of current 38, 176
Continuous and alternate-current windings 587
Continuous-current dynamos 399
Calculation of 353
Coupled in series 765
Continuous-current motors 482, 531
Convertible alternators 636
Converters (*see* Transformers)
Cooke uses electromagnet in dynamo 9
Cooling surface of magnet coils 373, 397, 622, 717
Copper—Amount expended on line 740
Deposition of 783
Heat waste per lb. 371
Specification of conductivity 786, 788, 790
Specific utilization of 368, 626
Copper and iron losses in transformers 700, 703, 715, 717
Cores of armature 41, 43, 44, 284, 451, 583, 602
Of rotor and stator 674
Of transformers 702
Core-disks 284, 367
Methods of driving 291
Toothed 286, 433, 544, 583
Pierced 290, 625, 674
Counter electromotive-force in motors 485, 496
In synchronous motors 649, 651
In transformers 697, 709
Couple (*see* Torque)
Coupling of alternators 647
Of dynamos 765
Couplings for direct driving 337
Cotton covering of wires 779
Creeping, magnetic 141
Critical current 209
Critical speed 210, 478, 525, 752
Crocker, F. B., on high voltage dynamos 466, 473
Crocker-Wheeler—Core-disks 287
Motors 533, 536

PAGE

Crocker-Wheeler—
Motor-generators 725
Self-oiling bearings 336
Crompton, R. E., on efficiency of dynamos 762
On end-connecting 307
On compound winding 57
On ring windings 301
On stranding conductors 299
Crompton & Co.'s dynamos 17, 401, 471
Cross-compounding 389
Cross-connecting ring armatures 275
Cross magnetization 70, 382, 679, 681
In motor 514
Current and torque 102
Current, alternating 547, 551
Current-carrying capacity of wires 779
Current-density, effect on heat waste 370
Permissible 340, 346, 370, 622, 779
Current in conductors, method of indicating direction of 73
Curve of integrated electromotive-forces 62, 66, 68, 78
Curves of magnetization 122
Cutting of magnetic lines 22, 27, 168, 475, 549, 675, 696
Cycle of alternating current 551
Of magnetization 133
Cylindrical winding, Brown's 310

D

Dal Negro, his machine 7
Motor 18, 485
Damp, effect of 769
Data of machines of various sizes 430
Data (*see* Tables)
Davenport's motor 18
Davidson's motor 18
Dead turns 88, 92, 206
De Bast, on rotatory-field motors 21
Definition of dynamo machine 1
De la Rive, on magnetic circuit 115
Demagnetizing effect of armature 70, 84, 353, 364, 380, 387
In motor 514, 530
In alternator 595, 654
In rotor 681
In transformer 698
Of eddy-currents 84, 515
Density of current 340, 346, 370, 622, 779
Of magnetic flux 115, 119, 342, 368, 430, 605, 715, 716

PAGE

Deposition of metals 468, 783
Deprez, Marcel, on characteristic curves 198, 200, 204
On compound dynamos 55, 239, 446
On constant potential dynamos 17
Design for dynamo 400
On field-magnets 161
On law of similars 109
Method of measuring power 757
On regulating motors 520
On theory of dynamo 20
On transmission of power 18
On two-phase combinations 663
Depth of winding 780
Deptford station plant 618
Derivation (*see* Shunt)
Design of dynamos 45, 339, 396
Of alternators 588
Of motors 531
Of transformers 715
Desroziers—Disk dynamo 43, 442, 480
Disk-winding 280, 282
Magnetic shunt 744
Developed winding diagrams 249, 597, 630
Diacritical current 144
Diameter of commutation 33, 78, 448
Of shunt wire 372
Difference of phase 556, 560, 571, 598, 649, 663, 709
Differentially-wound motor 522
Direction of electromotive-force 22
Of magnetic lines 113
Discoidal ring armatures 41, 284, 296, 417
Diseases of dynamos 83, 464, 772
Disk armatures 41, 43
Winding of 278
Of alternators 585, 614
Disk dynamo, Edison's 16, 279
Faraday's 5
Pacinotti's 15, 279, 479
Fritsche's 44, 279, 479
Desroziers's 43, 280, 442, 480
Disks for armature cores 284, 288
Distortion of magnetic field 69, 72, 74
Prevention of 388, 393
Distribution of potential on commutator 66, 68
Distributive winding 588, 626
Dobrowolsky, von Dolivo—Alternators 627

PAGE

Dobrowolsky, von Dolivo—
On bushed poles 393
On polyphase work 665
Double magnetic circuit 150, 160, 167
Douglas and Laxey railway plant 426
Douglass on early dynamo 10
Dove on magnetic circuit 115
Drag in case of embedded conductors 99
On armature by distorted field 75, 76
On conductors 96, 103, 486
Drawings, specification as to 786, 788, 790
Dredge, on theory of dynamo 4
Drehstrom 665
Driving horns 106, 296
Driving spokes 290
Drum armature 15, 41, 303
Design of 339
For alternators 583
Reaction of 76
Winding of 241, 255, 265, 302
Drying armature 300
Dub, on magnetic circuit 115
Du Bois, on magnetic properties of iron 127
Dujardin's "inductor" machine 10
Oscillatory dynamo 16
Du Moncel, Count, his early work 4, 10
Duncan and *Hassen*, on dynamo tests 764
Duncan, L., on alternate-current motors 21
Dynamo—As motor 18
Definition of 1
Parts of 2
Diseases of 83, 464, 772
Early forms of .. .. 5 *et seq.*
Management of 765, 769
Origin of word 13
Dynamometer 755
Dynamometric governors 521, 749

E

ECONOMIC coefficient 107, 185
Economy of transmission 735, 740, 742
Eddy-currents 90, 92, 299
Demagnetization due to 84, 515
Driving of motors by 665
Loss, calculation of 137

PAGE

Eddy-currents in transformer 689, 760
Edison, T. A., on auxiliary winding 394
On continuous-current transformation 727
Disk dynamo 16, 279
Early dynamo 16
Regulator 225
Standard dynamo 427
Method of end-connecting 325
Edison Co.'s dynamos 427
Edison-Hopkinson dynamo 421
Calculations of 353
Efficiency of 195
Effective volts and amperes 554
Efficiency calculations 347
Efficiency—Commercial 186
Electrical 185, 186
Of combined plant 762
Of dynamos 107, 185, 759
Of motors 487, 490, 497, 676
Of transformers, effect of wave form 712
Of transmission of energy 735, 740, 742
Testing 753
Specification of 787, 789, 791
Eickemeyer's armature winding 310
Dynamo 164
Electrical efficiency 347
Electric governing of motors 521
Electric motive power, theory of 489
Electric railway plant 424, 426, 540
Electro-metallurgy statistics 783
Electro-metallurgical dynamos 413, 468
Electromotive-force in moving conductor 22, 29
Addition of, in closed-coil armatures 61
Alternating 548
Average 174, 554
Of dynamos, factors of 45, 168
Fluctuation of 175
Of alternators 589, 590
In transformers 696
Electro-plating dynamos 8, 413, 468
Elliptically-rotating field 664
Elmore's electro-plating dynamos 469
Elphinstone, Lord, his multipolar drum 16
Elwell-Parker—Alternator 584
Electro-plating dynamo 470
Motor generators 725

PAGE

Embedding conductors in iron 99
Emission of heat at surface 373
End connectors 304
End play of shaft 331, 333
 Prevention of 333
End plates of armature core 293
Energy, where expended, where utilized 96, 487
Equations of dynamo 46, 170
 Of motor 494
 Of alternator 46, 549
 Of alternator as motor 658
 Of asynchronous motor 684
 Of transformer 696, 699, 722
 Of motor generator 728
Esson, W. B., on armature reaction 72, 382, 384
 On arc-lighting dynamos 465
 On binding wires 297
 On load curves 381
 On multipolar machines 21, 396
 On permissible heating 373
 On peripheral speed 367, 375
 On size and output 110
Ettingshausen's machine 8
Evershed, on transformer design 716
Evolute connectors 305
Ewing, on magnetic properties of iron 127, 129, 135
 Magnetic tester 137
 Method of exploring commutator 66
Excitation of field-magnets 47, 52, 56, 197, 210, 224, 594
 Of synchronous motors 652
Excite, dynamo fails to 776
Exciting current in shunt 370
Exploring electromotive-force of armature 63, 73
External characteristics 202, 210
Extra-high-pressure dynamos 473

F

FAILURE to excite 776
"Falcon" dynamos 419
Faults in armature 772
 In field-magnet coils 776
 Of alternators 776

PAGE

Faraday, Michael—Discovers induction 1, 3, 22
His disk dynamo 5
Electromagnetic rotations 17
His researches 5, 6, 7
On magnetic circuit 115
On magnetic lines 26
His ring 695
Farmer, Moses G., on self-excitation 12
Favre's researches 19
Feathers 337
Fein's dynamos 406
Feldmann, on alternating-current wave form 713
Ferranti's alternators 16, 585, 586, 613
Mains, capacity effect 566
Rectifiers 731
Transformers 707, 714
Ferraris, Galileo, on magnetic rotation 21, 664, 665
On monophase motors 690
Feussner, on parallel running 766
Field—Concentration of 393
Magnetic 113
Field-magnets 34
Advantage of powerful 95, 380
Branched 119, 153, 159, 473, 601, 629
Design of 341, 344, 378
Excitation of 47, 52, 56, 197, 210, 224, 594
Forms of 158, 378
Formulæ for 143
Of motor 515
Finzi, on hysteresis 141
Fischer-Hinnen, on armature compensation 391
"Flashing over" 83, 464
Flats on commutator 775
Fleming, J. A., on alternating currents 552
On alternate-current wave form 712
On capacity-effect in mains 566
On finding form of wave 553
On measurement of alternate-current power 568
On loss in transformer iron 137
On reluctivity 144
Rheostats 744
Rules as to force on conductors 22, 96
On transformers 552, 712, 713
Fluctuations of electromotive-force 173, 464
Flux-density 115, 119, 120, 342, 368, 430
In alternators 605

PAGE

Flux density—
    Calculation of .. 348, 360, 364
    Effect on losses in armature .. 762
    In multipolar machines .. 397
    In transformers .. 138, 715, 717
Flux—Magnetic .. 114, 143
    Regulation of .. 744
Fontaine's transmission of energy .. 734
Fontaine and Gramme, transmission of power .. 18
Fonvielle, on rotation of iron disk .. 687
Forbes, Prof. George, on carbon brushes .. 319
    Designs for Niagara plant .. 636
    On homopolar dynamo .. 476
    On transmission of energy .. 741
Force on conductor in magnetic field .. 3
Form of wave of alternating currents .. 549, 711, 713
Formulæ for the electromagnet .. 143
Foucault currents .. 90
Foundations .. 769
Foundation ring for armature .. 284, 291, 417
Fourier's series .. 569
Frankfort—Central station plant .. 634
    Exhibition tests .. 764
    Transmission .. 741
Frequency .. 549, 560, 574
    High .. 570, 578
    Usual .. 579
Friction .. 106, 332
    Measurement of loss by .. 761
Fringe of field .. 81, 155, 355, 361, 393
Frith, on flux regulation .. 744
Fritsche, on armature winding .. 21, 244, 272
    On disk winding .. 280, 480
Frölich, Dr. O., on armature reaction .. 86
    On characteristic curves .. 200
    On compound motors .. 528
    On electromagnet .. 143
    Equations of electromagnet .. 20
    On eddy-currents .. 90
    On Siemens' dynamos .. 405
    On size and output .. 109
Froment's motor .. 18, 484
Froude's brake dynamometer .. 755
Full load, calculations at .. 363

G

PAGE

Gaisberg on armature distortion 69
Ganz's dynamos 406
Ganz-Zipernowski alternators 611
Gap in magnetic circuit—Effects of 128
Thickness of 387, 398
Widening of 379
Gaugain, J. M., on curves of integrated electromotive-forces .. 4, 62
Gauge of wire for armature 342, 346, 369, 779
Gauss, the 119, 144
Gauze for brushes 318
General Electric Co.'s Alternators 626
Dynamo 432
Railway motors 546
Genoa transmission of power 736
German-silver, use of 622, 785
Gilbert, the 144
Goerges on output of polyphase machines 601
Gold, deposition of 784
Goolden & Co.'s Brush-holder 325
Dynamos 434
Mining motor 539
Regulator 745
Goolden-Willans plant, test of 764
Gordon's alternators 16, 599, 607
Governing—By steam-pressure 749
Dynamometric 749
Government of motors 519
Governors 226, 463, 625, 743, 748
Gramme—Alternator 580, 582
Armature 15, 41
Dynamos 400
" characteristic of 206
Motor generator 724
On coupling of series dynamos 767
Transmission of power 18
Graphic treatment in alternate-current work 561
Of asynchronous motors 682
Of continuous-current motors 496
Of dynamos 66, 196, 239
Of monophase motors 692
Of transmission 738
Of synchronous motors 652
Gülcher Co.'s brush-holder 322
Commutator 315
Gyrostatic action of armature 328

H

PAGE

Hagenbach on theory of dynamo 20
Heat, effect of, on magnetization 131
Heat, waste in polyphase motors 677, 678
Heating and surface emission 373, 717
Of armatures 295, 372, 773
Of cores 90, 137, 715
Of magnet coils 369
Of pole-pieces 70
Of wires 782
Specification of maximum 752, 785, 788, 790
" Hedgehog " transformer 707, 714, 717
Hefner Alteneck (*see* Alteneck).
Helios Co.'s alternator 611
Helmer, design of 473
Heilmann locomotive dynamo 415
Heinrichs' dynamometer 756
Heisler's constant-current alternators 640
Henley's inductor dynamo 10
Henry's motors 17, 483
Henry, the 560
Hering, Carl, on armature winding 21, 244
On homopolar induction 478
On magnetic leakage 152
Herrick, on rheostats 744
Herwig, on theory of dynamo 20
Heteropolar dynamos 475
Heteropolar induction 475
High frequency 570
Skin effect 578
High voltage—Dynamos 473
Commutators for 446, 465, 473
In transmission 694, 732
Historical notes 5
Hjorth, Sören, his machines 11, 56
Hochfelden transmission 738
Hochhausen's designs 400
Holes in core-disk 99, 286, 290, 604, 625, 628
Holmes's dynamos 10
Holmes, J. H. & Co.'s, dynamos 436
Holmes-Willans combined plant, efficiency of 762
Homopolar dynamos 475
Homopolar induction 5, 475
Hoppe, on homopolar induction 478

PAGE

Hopkinson, Drs. J. and E., on dynamo design 20, 421, 423
On excitation by backward lead 87
On alternators 612
On magnetic circuit 145, 153
Hopkinson, Dr. J., on armature reaction 382
On coupling alternators 21, 573
On characteristic curves 198
Electro-plating dynamo 470
On loss of power in magnetization 140
On magnetic properties of iron 122
On magnetic calculations 117
Method of end connecting 306
Modification of Edison dynamo 353, 421
On railway motors 545
On retardation of magnetism 142
On reversing gear 518
On size and output 108
On testing dynamos 758
On theory of alternate currents 573
On theory of transformers 719
On torque of motors 509
Horns, or pole tips 80, 93, 393
Horns, driving 296
Horse-power of dynamos and motors 102, 531
Horse-power, testing 753
Hospitalier, E. 242
Housman, on armature compensation 389
On separation of losses 761
Houston, E. J. (*and see* Thomson-Houston) 458
Hummel, on causes of losses 764
Humphrey and Powell, on transformer-current curves 711
Hunt, R., on electromagnetism as a motive power 484
Hurmuzescu's dynamo 473
Hutin and Leblanc, on alternate-current motors 21
Alternating-continuous transformer 729
Ammortisseur 392
Hysteresis 106, 133
Loss 135, 137, 760
Increase of, with time 142
In transformer 698, 712, 715, 717
Hysteretic constants 137

I

PAGE

IDLE coil 67, 449
Idle current (*see* Wattless current)
Idle wire 41, 420
Imbricated conductors 402
Imbricated joints in iron 707
Immisch's motors 532
    Reversing gear for 518
Impedance 562
Impressed field 678
Indicator diagrams 753
Inductance 560
Induction coil 695
Induction of electromotive-force 1, 3, 22, 24, 29
Induction in uniform field 61
"Induction," magnetic (*and see* Flux-density) 120
Inductor alternators 10, 640
Instantaneous value of electromotive-force 549
Insulating materials—Air 315, 705
    Asbestos 44, 314, 614, 629, 771
    Canvas 294, 432, 452
    Cotton 779
    Cotton cloth 452
    Ebonite 322, 325, 326, 429, 619, 623, 707, 708
    Enamel 291, 299, 621
    Fibre, hard white 296, 314, 324, 432
    Film of oxide 285, 299
    Film of oil 299
    Glass 616
    Indiarubber 294, 533
    Insulating paint 294
    Ivory 485
    Japan 294
    "Made mica" 429
    Mica 44, 284, 294, 314, 429, 614, 623, 771
    Muslin 429
    Oil 429, 705
    Oiled linen 431
    Paper 294, 302, 451, 705
      " core-papers 429
      " Manilla 294
      " oiled 431
      " paraffined 294
      " parchmentized (Willesden paper) 294, 314, 533
      " pressed board 429
      " varnished 285, 294, 451

PAGE

Insulating materials—
Plaster 314
Porcelain 616
Rope, hard 429
Rubber varnish (Scott's) 294
Shellac 314, 358, 451
Silk 299, 623
Slate 621, 623
Sulphur 616
Tape 285, 301, 425, 431, 621, 705
Varnish 44, 285, 294, 429, 451, 705
Vulcanized fibre 614
Wood 290, 296, 614, 703
Insulation of armature cores 42, 284, 294
Of brush-holder 324
Of collecting rings 326
Of commutator 314
Of dynamo from ground 774
In transformers 703
Of wires 779
Insulation resistance 752
Specification of 786, 788, 790
Insulation tests 772
Intensity of magnetic field 113
Interchangeability of parts 785, 787
Interference of armature (*see* Armature reaction)
Isenbeck, on armature exploration 63
On curves of integrated electromotive-forces 62
Iron and copper losses in transformers 700, 715, 717
Iron in armature of alternator 593, 602
Iron, magnetic properties of 112, 122
Iron (*see* Armature, Cores, Flux-density, Hysteresis)

J

Jackson, Prof. D. C., on magnetic properties of iron and steel .. 127
Jacobi, on back electromotive-force of motors 485
On early dynamo 8
On electromagnet 143
On law of maximum output 491, 494, 498
Law of, applicable to alternators 656
Motor 18, 483
Jamin and *Richard*, on theory of alternate currents 573
Jehl and *Rupp*, disk dynamo 480
Jehl, on continuous-current transformation 727

PAGE

Johnson & Phillips—Kapp's dynamos 359, 403, 607
Transformers 705, 714
Johnson, on early dynamo 11
Joints in magnetic circuit 129
Joubert, on finding form of wave 552
Method of exploring commutator 63, 65
On spurious resistance 89
On theory of alternate currents 573
On theory of dynamo 20
Joule, J. P., on back electromotive-force of motors 486, 491
On electromagnet 143
On magnetic circuit 115
Law of 493
Motors of 483
Joule's researches 19
Journals 328
Joyce, on heating of conductors 376

K

Kapp, Gisbert—Alternators 552, 582, 607
Brush-holder 324
Commutator 315
On depth, &c., of winding 782
Dynamos 402
Dynamo, calculations of 357
Efficiency of 195
On dynamometry 755
On leakage in line 499
On limits of load 386
On magnetic calculations 117
On magnetic circuit 145
On method of driving core-disks 292
On method of end-connecting 307
On separation of losses 760
On size and output 109
On testing dynamos 759
On theory of dynamo 21
On transmission of energy 509, 740
Transformers 705, 714
On width of pole-faces 588
Kelvin, Lord—Alternators 16, 613
Disk dynamo 479
On efficiency of motors 491
On theory of dynamo 20
On theory of homopolar dynamo 478

PAGE

Kelvin, Lord—
On transmission of energy 740
On wave winding 596, 613
Kennedy, A. B. W., test of combined plant 762
Kennedy, Rankine—Ironclad dynamo 162
Alternators 582
Polyphase motors 687
Kennelly on armature reaction 86
On reluctivity 144
Keys 337
Kingdon's inductor alternator 640
Kohlrausch, on armature distortion 69
On theory of alternate currents 573
Curves showing armature reaction 69
Kolben, Oerlikon dynamos 408
Koosen, on theory of alternate currents 573
Investigations 19

L

Ladd's self-exciting dynamo 14
Lag of current 558, 561
Effect on torque 571
Lag effect of demagnetizing 596
Lag, magnetic 141
Lahmeyer—Dynamos 162, 441
On "far-leading" dynamos 725
Laminated series motors 693
Lamination of armature conductors 91, 299, 342
Of armature core 44, 91, 284, 451, 583, 609, 625, 673
Of pole-pieces 91, 602, 636, 643
Lamont, on electromagnet 143
Lap-winding 253, 279, 596
Lauckert's compound winding 57
Lauffen generator 627
Lauffen transmission 741
Laurence, Paris & Scott's motor generators 724
Law of action and reaction 487, 516
Of efficiency of motor 491, 498
Of hysteresis 137
Of Lenz 516
Of magnetic circuit 114, 145
Of maximum output of motor 491, 494, 498, 656
Of Ohm 23
Of transformer 699

PAGE

Lead of current 558, 561, 564, 566
Caused by synchronous motor 654
Effect on field 596, 654
Lead of brushes 72, 76, 78, 85, 382, 448
„ backward 395, 396
„ in motor 514
"Leading" polar horn 76, 94, 382
Leakage in line 499
Leakage, magnetic 150
Leblanc (*see* Hutin and Leblanc)
Lecher, on homopolar induction 478
Ledeboer, on parallel running 766, 768
Leicester central station plant 622
Length and diameter of armatures 92, 342, 377
Length of conductor per volt 476, 622
Lenz, on dynamo as motor 18
On electromagnet 143
Law of 516
Researches 19
Le Roux, on theory of dynamo 19
On theory of alternate currents 573
Lightning arresters 774
Limit of armature current 381, 386
In multipolars 396
Linde, on finding form of wave 552
Line, integral, of the magnetic forces 118
Lines—Magnetic 113
Of force as distinguished from magnetic lines 114
Of magnetic induction 120
Liverpool overhead-railway plant 545
Load on dynamo, limit of 381, 386
Locomotive motors 540, 545, 546
Lodge, Oliver J., on impedance 562
London Electric Wire Company's data 779
Lontin's machine 15, 43
Loomis, on the location of armature faults 775
Loss of power in magnetic cycle 135, 139
In transformer 700, 715, 717
Losses, separation of 760
Lost amperes 190
Lost volts 180
Calculation of 345
Lubrication of bearings 334, 619, 624
Of commutator 771
Lubricators 334
Lummis-Paterson, on dynamo management 772

M

PAGE

MAGNET coils, heating of 369
Magnets, forms of 158
Magnetic calculations 348, 356, 361
Magnetic circuit 114, 145
Air gap in 128
Joints in 129
Branched 119, 150
Calculations of 350, 356, 361, 364
Reluctance of 119, 120
Magnetic—
Conduction 118
Creeping 141
Cycle 134
Field about conductors 24, 98
„ rotating 266
„ stiffness of 393
Flux 114, 168
„ calculations of 348
Leakage 150
„ allowance for 349
„ in asynchronous motors 681
„ measurement of 153, 752
„ in transformers 700, 704
Lines 24, 28
Permeability 120, 349
Potential 116, 119
Potential in gap 384
Principles 112
Properties of iron and steel 124
„ „ changes of 142
Pull on armature 328
Retardation in solid coils 141
Shunt 530
Units 112, 144
Magnetizing coil 117
Magnetizing current in transformer 698, 709, 715
Magnetization of armature 70
Magnetomotive-force 116, 117, 145
Magneto-electric machine 33, 48
Theory of 179
Magneto-ringer 548
Magnolia metal 333
Main's alternators 624
Malderen's machine 10
Management of dynamos 765, 769

PAGE
"Manchester" dynamo 420
Manchester street station plant 625
Maquaire's regulator 745
Martin and *Wetzler*, on motors 484
Mascart and *Joubert*, on size and output 108
Mascart, on theory of dynamo 20
Masson's improvements 10
Mather, on armature compensation 389
Mather and Platt—Alternators 612
Car motor 544
Railway motor 545
Dynamos 420
Equalizers 726
Mavor and Coulson—Dynamos 438
Mining motor 540
Maximum—Armature current 331, 386, 396
Power of synchronous motor 655
Values of sine functions 554, 564
Maxwell, J. Clerk, on self-exciting machines 19
On self and mutual-induction 719
On theory of alternate currents 563, 573
On theory of transformers 721
Mean power, alternate-current 566, 571
Measurement of alternate-current power 567, 568, 571
Of efficiency 758
Of fluctuation of electromotive-force 178
Of insulation resistance 752
Of magnetic leakage 752
" properties of iron 127
Of power 753, 758
Of resistance of armature 751
Of total flux 178
Mechanical actions and reactions 96
Mechanical characteristics 502, 528
Mechanical points in design 327
Mesh connection of polyphase circuit 669
Menges, on armature compensation 391
On dynamo testing 758
Meyer, on theory of dynamo 20
Meylan, on parallel running 766
Mild steel, magnetic properties of 123, 127
Minet, on dynamo tests 764
On Edison dynamos 427
Mitis metal 127
Moncel (*see* Du Moncel)
Monophase motors 687

PAGE

Mordey, W. M., on alternate-current wave form 713
On alternator curve 553
On armature exploration 64, 66
On coupling compound dynamos 767
On finding form of wave 552
On motor and dynamo analogies 516
On parallel working 21
On the shunt motor 529, 530
On slow changes in iron 142
On synchronous motors 653
Alternators 619
Inductor alternators 641
Method of cross-connecting 276
Methods of exploring commutator 63, 66
Multipolar ring 16
Transformer 702, 714
Victoria dynamo 417
Morin's dynamometer 756
Motors—Action of alternator 571
Alternate current (*see* Alternate-current motors)
Asynchronous 362
Characteristics of 505
Commutation in 517
Continuous current 482, 531
Determination of windings 527
Direction of rotation 517
Efficiency of 487, 490, 498
Historical notes 17
Laminated 693
Monophase 687
Polyphase 21, 662, 673
Pulsating 546
Regulation of 519
Reversal of 517, 518
Rotatory-field 666
Speed of 501, 503
Theory of 492
Torque of 501, 503
For traction purposes 540
Motor-generators 724
Mountain, W. C., commutator 322
Müller—Disk winding 279
Method of measuring power 757
On electromagnet 143
On magnetisation of steel 10
Multiphase (*see* Polyphase)

PAGE
Multiplex windings 272
Multipolar—Brush dynamo 457
Dynamos, design of 396, 580
Drum winding 265
Ring for alternators 581
„ windings 275
Polyphase plant 672
Murray's dynamometer 756
Tests of brush dynamo 458
Murray, on self-excitation 12
Mutual induction 94, 719

N

Negro (*see* Dal Negro)
Neumann, on laws of induction 19
On theory of alternate currents 573
Neutral point on armature shifted 70
Neutral points on commutator 77, 78, 257, 320, 515
Newall, on joints in magnetic circuit 129
Niagara plant 636
Niagara transmission 737
Niaudet, Alfred, on theory of dynamo 4
On gramme dynamos 401
Nickel, deposition of 784
Noise in running 777
Nollet's machine 10
Non-concentric poles 394
"Non-polar" dynamo 476

O

Oerlikon Co.—Alternators 627
Drum armature 307
Dynamos 408
Electro-metallurgical dynamos 472
Polyphase motors 673
Transformer 704, 706
Oerlikon works, transmission of power to 736
Ohm, Dr. G. S., law of 23
Oil (*see* Lubrication).
As insulator 429, 705
Insulators 742
Open-coil armature 40
Advantages of 464
Open-coil dynamos 447

PAGE

Organs of dynamo 31
Oscillatory dynamo 16, 427
Output and size 102, 108
Output of alternators 589
Over compounding 237, 239, 728
Over-excited synchronous motor 654
Overload 786
Over-type, support of armature in 327

P

Pacinotti—Armature 13, 14, 16, 41
Disk dynamo 278, 479
Motor 18
Toothed core 286
Page—" Inductor " machine 10
Motor 18, 483
Paper (*see* Insulating Materials)
Parallel—Alternators in 647, 659
Coupling machines in 766
Paris and Scott's method of end-connecting 307
Parker's dynamo 437
Parshall's multipolar dynamos 434
Parsons—Turbo-alternators 624
Steam turbine, efficiency of 624, 763
Paterson and Cooper—Core-disks and spider 291
Dynamos 439, 470
Pedestals 332
Peripheral speeds 109, 299, 367, 476
Period 549
Periodic governor 521
Periodicity 549
Permeability 120, 349
Curves for iron and steel 125
Permissible heating 752
Perry, John (*see* Ayrton and Perry)
Ring winding 276
Constant-speed motors 18
On shaft stresses 331
On theory of transformers 723
Pescetto, on size and output 108
Petrina's machine 8
Peukert, on armature reaction 87
Phase of alternation 550, 555
Phase-difference 649
Phase-relations in transformers 708

PAGE

Phase-splitting 689
Phase transformation 731
Picou, R. V., on rotatory-field motors 21
On self-governing of motors 529
On synchronous motors 21 652, 655
Pitch 588
Pixii, his machines 7
" Phœnix " arc-light dynamo 465
Dynamo, particulars of 366
Plücker's homopolar dynamo 475
Poggendorff—Commutator 8
Investigations 19
Polar-span, angle of 74, 387, 588
Pole armatures 41, 584
Pole-pieces—Eddy-currents in 92
Effect of shape on wave form 569
Lamination of 91, 602, 636, 643
Varieties of 393, 394
Pole-faces, width of 588
Pole surfaces, shaping of .. 68, 83, 95, 160, 388, 391, 393, 394, 471, 552
Pollak's rectifying commutator 731
Polechko's dynamo 481
Polyphase and single-phase alternators 601
Polyphase—Alternators 598
Motors 21, 662, 673
" history of 19
" theory of 21, 675
Transformers 718
Poncelet's improvement of Prony brake 754
Ponemah Cotton Mills plant 661
Posit'on of dynamo 769
Potential at terminals 180
Potential, magnetic 119
Potier, on rotatory-field motors 21
Power—Alternate-current 566, 571
Characteristic 200
Mean, of alternate currents 577
Measurement of 753
Of polyphase motors 676
Of synchronous motor 650, 652
Product of two factors 100, 493
Power-factor of transformers 709
Practical construction of armatures 284
Pressure on bea rngs 327
Preston, T., on homopolar induction 478
Prevention of sparking 80

PAGE

Primary and secondary currents 695
Products of periodic functions 557
Prony's brake 754
Puffer, on parallel running 766
Pulley, overhung 330
Pulsating motors 546
Pulsation 574
Pulvermacher's machine 8
Pyke and Harris's indicator alternator 642
Pyke and Salomons transformer 702

Q

Quadrature 557
Quarter phase 557

R

Racing of motors 519
Racking of armature conductors 185, 317, 572, 777
Of connectors 317
Radian, unit angle 101, 173
Raffard's improvement of Gramme dynamo 400
Of Prony brake 755
Railway, electric, machinery for 424, 443, 540
Ratio of transformation 697, 720, 727
Ravenshaw 434
On dynamo testing 758
Regulator 747
Raworth—Method of exploring commutator 66
Coupling 338
Rayleigh, Lord, on alternate currents 573
On dynamo testing 758
Reactance 560, 566
Reaction (*see* Armature reaction)
Reaction due to current in armature 58, 70, 382
Reaction—Mechanical 96, 317, 572
Of inductance 559
Of motor armature 510, 513
Reber, on polyphase motors 21
Rechniewski, on continuous-current transformation 727
On size and output 109
Reckenzaun, on motors 532
Rectification of currents 38, 172, 449, 594, 728
Rectifying commutators 594, 728
Regulating dynamo, ways of 49, 51, 461, 743
Regulating resistance, specification of 785, 788

PAGE

Regulation of motors 519
Of Parson's turbine 625
Of Thomson-Houston dynamo 461
Regulators 748
Reignier, on regulators 748
Relation between size and output 340
Reluctance of magnetic circuit 116, 118, 119, 120, 145
Reluctance, calculation of 350, 356, 361, 364
Reluctivity, a linear function of H 144
Remanence 132
Renshaw's spherical bearings 333, 334
Residual magnetism 132
Resistance—Effect of, in rotor 681
For regulating 226, 445, 744, 747
In characteristic 206
Insulation 752
Of coil, relation to size 377
Of shunt coil 370
Of wires 782
Spurious, in armature 89
Resultant magnetic flux 675, 678
Retardation of phase (*see* Lag)
Of magnetism 141
Retarded field motors 693
Reversal of current in armature coils 80
Of motor field 517
Of polarity 50, 469
Reversibility of dynamo 18
Reversing gear of motor 518
Rheostat as regulator 226, 445, 744, 747
Rheostat, specification of 785
Rhodes, on synchronous motors 21, 659
Richardson's governor 748
Right hand rule 22
Rimington, on alternate current-wave form 712
Ring armatures—Cross-connection of 276
Winding of 37, 40, 71, 251, 258, 275, 580
Magnetization of 71
For alternators 580
Series connecting in 276
Pacinotti's 13, 14
Gramme's 15
Multipolar 275
Ritchie—His machines 8, 10, 18, 483
On magnetic circuit 115
Robin's disk dynamo 480

PAGE
Rockers 78, 322
Rocking of brushes 78, 771
Roessler, on alternate-current wave form 713
Romilly, on drum winding 15
Rotatory magnetic field 662, 666
Rotor 674, 668
In alternating field 688
Effect of resistance in 681
Of Stanley-Kelly motor 687
Rowland, on relation between magnetomotive-force and flux .. 116
Rücker, on limits of regulation 21, 242
Rupp, on continuous-current transformation 727
Disc dynamo 480
Ryan, Prof. H. J.—Method of exploring commutator 66
On armature compensation 391
On synchronous motors 21
On transformer-current curves 711

S

Sahulka, on alternate-current motors 21
Salient poles 161
Sandwiched coils in transformer 701
Saturation, magnetic 121
In compound machine 232
Sawyer's inductor dynamo 10
Saxton's machine 8
Disk dynamo 479
Sayers—Boosters 726
"Commutator" coils 394, 395
Dynamos 438
Electro-plating dynamo 471
Mining motor 540
On motor commutation 515
On parallel running 766
Schellen, on theory of dynamo 4
Schönenwerth plant 632
Schuckert & Co.—Continuous-alternating transformer 731
Dynamos 440
Schültz, on armature reaction 86
Scott and Mountain 582
Secondary and primary currents 695, 709
"Section" of a winding 60
Self-compensating armatures 394
Self-exciting dynamo 49

PAGE

Self-exciting alternators 594
Self-governing motors 522
Self-induction 560
Effect of, in synchronous running 650, 660
In alternators 606
In circuit with transformer 710
Causes sparking 79
Self-oiling bearings 336
Self-starting synchronous motors 661
Sellers, Coleman—Designs for Niagara plant 636
On double lubrication 335
Sellon, on continuous-current transformation 727
Separate coils for excitation 52
Separately-excited dynamo 48, 594
Theory of 179
Separation of losses 760
Series-connecting in ring armatures 276
Series dynamo 49
Characteristic of 197, 204
Efficiency of 188
Coupling of 765
Series lighting 445
Series motors—Characteristics of 506
In transmission 509
Series-winding on motor 524
Series-winding not to be used with electro-plating dynamos .. 469
Shaft, design of 329
Shaping of pole-pieces .. 68, 83, 95, 160, 388, 391, 393, 394, 471, 552
Shell-transformers 702
Short-circuits in armatures 773
Shunt coil calculation 372
Heating of 370
Shunt current, calculation of 346, 370
Shunt dynamos 50
Efficiency of 190
Coupling of 765
Shunt motor—Characteristics of 510
Constancy of speed 529
Shunt and series winding on motor 527
Siemens, Alexander, on torque of motors 508
On shunt dynamo 211
Siemens, Sir William—Efficiency of motors 491
Early researches 11, 16
On transmission of power 490, 510
On shunt dynamo 210
On compound winding 57

PAGE
Siemens, Werner von—Self-exciting dynamo 13
On armature reaction 86
Mining drill 546
Shuttle-wound armature 11, 33, 469
Invents name of dynamo 13
On transmission of power 491
Siemens—Alternating-continuous transformers 728
Alternators 609
Dynamo (old) 15, 33, 158, 469
Dynamo (new) 404
„ characteristics of 196, 201, 211
„ efficiency of 195
Homopolar dynamo 475
Mining drill 546
On efficiency of motors 491, 492
Law of 493
Winding 303
Siemens and Halske—Alternators 609
Brush-holder 325
Dynamos 163, 302, 367, 397, 406
Electro-plating dynamos 469
Ring dynamo 163
Silver, deposition of 783
Silver solder 305, 610
Sine curve 37, 62, 548, 550, 553, 569, 713
Sine-curve controversy 553, 569, 713
Single-phase motors 687
Sinsteden—Self-exciting dynamo 10
On theory of dynamo 19
Size of dynamo in relation to output 108, 340, 377
Size and output in relation to cooling surface 376
Skin-effect 578
Slater Lewis' regulator 745
Sleeve for armature 292, 332
Sliding contacts 5, 35, 312, 326, 384, 475, 585, 630, 673
Sliding rails 769
Slip in asynchronous motors 666, 675, 678, 679, 681
Slip in monophase motors 688, 691
Slip-rings (*see* Sliding contacts)
Slotted armature 343
Smith, Rev. F. J.—Method of measuring torque 185
On work-measuring machines 755, 756
Smith, Holroyd, his brush 321
Smith, Willoughby, on homopolar dynamo 476
Snell—Motors 533
On horse-power of motors 531

PAGE
Snell, on size and output 386
South London Electric Railway plant 424
Spacing in armature winding 246, 256
Sparking—Causes of 78, 381, 450, 771
Prevention of 80, 381, 387, 397, 450, 514, 771
Specification of alternators 787
Of dynamos 785
Of transformer 789
Specific utilization of copper 368
Speed—Dependence of volts on 21, 45, 173, 346, 476, 549
Advantage of high 47, 369
Peripheral 109, 299, 367, 476
Regulation of shunt motor 511
Relation of, to characteristic 205
(*See also* Critical speed *and* Slip)
Sperry's arc-light dynamo 465
Spherical armature 458
Spherical bearings 334, 434, 628
Spiders 290, 332
Spiral winding 596
Split-phase motors 689
Splitting the phase 689
Sprague, F. J.—Motors 534, 536
On motor regulation 522
Spurious resistance 89
Square-root-of-mean-square 554
Squirrel-cage rotor 667
Stafford and Eaves' electro-plating dynamo 470
Staggered poles 686
Stampings for cores 286, 583, 674, 702
Stanley's constant-current alternators 640
Stanley-Kelly—Inductor alternators 641
Two-phase motor 686
Star connection of polyphase circuit 663
Starting—Dynamo 769
Of motors 509
Torque of asynchronous motors 680
Stator 668, 674
Statter's arc-light dynamo 465
Steam consumption, test of 762
Steel, magnetic properties of 123, 134
Steinmetz, on alternate-current wave form 712
On asynchronous motors 685
On polyphase motors 21
On loss by hysteresis 137
On synchronous motor 21, 659

PAGE

Step-up transformers 694, 737
Stiffness of field 393
Stohrer—Disk dynamo 479
Machine 8
Storch, on size and output 109
Stranded copper conductors 299
Stray field 150, 152
Stray power 105, 758
Street-tramway generator 433
Stress, effects of, on magnetism 294
Stresses in shaft 331
Stroh, A., constructs self-exciting dynamo 13
Stromberg, on armature reaction 86
Sturgeon—Machine and commutator 8, 33
On magnetic circuit 115
Wheel 483
Summation of electromotive-forces 591
Sunk windings 284, 286
Surface of heat emission 373
Surface windings 284
Swinburne, James, on armature exploration 64
On armature reaction 382
On armature compensation 389
Dynamo designs 262
On dynamo testing 758
Method of end connecting 307
„ exploring commutator 63
Transformers 707, 714, 717
Synchronizer 659
Synchronizing alternators 659
Synchronous motors 21, 647
Variation of excitation of 652, 656
Synchronous polyphase motors 660
Symbols, table of 169

T

TABLES—Of binding wires of Edison dynamos 297
Of circuits of Brush dynamo 456
„ Thomson-Houston dynamo 462
Of constant-speed generator and motor compared 523
Of cross-sections for different shapes 378
Of current and volts of Siemens' machine 108
Of data of A.E.G. motor 538
„ of Crocker and Wheeler's motors 538
„ of Edison dynamo 430, 431

PAGE

Tables—
Of data of Edison-Hopkinson dynamo 354
„ of Elwell-Parker continuous-current transformer .. 725
„ of Kapp dynamo 357, 358, 363
„ of Sprague motors 535
„ of Westinghouse Co.'s street-car motors 543
Of effect of joints in wrought iron 130
Of efficiency test of Goolden-Willans plant 436
„ „ Snell motor 533
Of electro-metallurgical data 783, 784
Of flux-densities in dynamos 368
Of flux through various parts of Lahmeyer's dynamo .. 153
Of heat waste at different current-densities 371
Of hysteretic constants 137
Of hysteresis waste 140
Of journal sizes 330
Of leakage coefficients 151
Of motor speeds and currents 488
„ torque and currents 507
Of pole width of alternators 589
Of shunt-motor speeds 529
Of symbols 169
Of transformer data 714
„ relations 720
Of triplex two-pole drum winding 274
Of values of B and in iron 126
Of winding of Lauffen three-phasers 629
„ on Siemens' plan 260
Of two-pole drum winding 247
Of two-pole symmetrical winding 265
Of four-pole drum winding 269
Of eight-pole drum winding 268
Of lap winding 255
Of wave winding 255
Wire gauge and amperage 780, 783
Tape (*see* Insulation)
Tatham, on dynamometry 756
Teazer coils 56, 451
Teeth of armature cores 14, 43, 99, 287, 343, 602
Produce eddies in pole-pieces 93
Temperature rise (*see* Heating).
Terminal potential difference 202
Tesla, Nikola—High frequency 570
On polyphase work 665
Split-phase motors 689
Two-phase motor 671

PAGE
Testing dynamos 751, 763
Specification of 787, 789
Testing—For faults in armature 752, 773
Insulation resistance 752
Temperature-rise 752
Tests of car motor 542
Theory of compound-wound motors 522
Of continuous-current transformation 727
Of dynamo 19, 22, 45, 168
„ alternate current 573
„ series wound 188
„ shunt wound 190
„ compound wound 224
Of electric motive power 489
Of monophase motors 690
Of polyphase motors 675
Of the synchronous motor 648
Of transformer 699, 708, 719
Thickness of core-disks 284
Third brush for shunt coil 52
Thompson, M. E., on armature distortion 69
Thompson, S. P., on armature exploration 63
Method of compensating armature 390
Thomson, Elihu, on armature compensation 389, 391
On breadth of alternator coils 590
On continuous-current transformation 727
On dynamometric governing 749
Experiments with alternating current 687
His inductor 642
His open-coil dynamo 16
On transformer conductors 717
On constant-current transformers 717
Thomson-Houston—Dynamo 458
Transformer 714
Thomson, James, on brake dynamometer 755
Thomson, Joseph J., on joints in magnetic circuit 129
On skin-effect 578
Three-dynamometer method 568
Three-phase alternators 599, 604, 627, 644
„ convertible to single phase 636
Combinations 664
Currents 600, 665, 670
Inductor alternator 644
Three-voltmeter method 568
Three-wire system, transformers for 718
Thrust bearings 333

PAGE
Thurston, on Brush dynamo 458
Thury—Continuous-current machines for transmission 736
Dynamos 442
Inductor alternators 646
Regulator 745
Timmermann, A. H., and C. E., on radiation of heat 376
Tooth (*see* Teeth).
Torque of alternators 571
Of armature 96, 100, 102
Constant 749
Of asynchronous motors 676, 681, 685
Of monophase motors 691
Of motors 501, 503
Of synchronous motor 650
Traction motors 540, 545, 546
"Trailing" polar horn 76, 94, 382
Tramway generators 433
Transformers 694
Construction of 700
Continuous-current 724
Design of 715
For constant current 717
For insulation tests 752
Modern types 702
Polyphase 718
For three-wire systems 716
Specification of 789
Transformer-action of polyphase motor 676
Transformer-cases, specification of 790
Transmission dynamometer 755
Transmission of energy 732
At high voltage 694
By alternate currents 647, 651
By polyphase currents 668
Two-series motors in 509
Triplex-winding 273, 274
Trotter, A. P., on magnetic leakage 153
On motor regulation 530
Regulator 747
True watts 567
Turbo-alternator 625
Two-phase—Alternators 599, 634
Combinations 663, 670
Currents 600
Motors 661, 666, 671, 673, 686
"Tyne" dynamo brush-holder 322

U

PAGE

UNDER-TYPE, support of armature in 327
Unipolar dynamo 6, 475
Units, connections between 101
Units, magnetic 112, 144
Unwin, on brake dynamometer 755
Uppenborn, on compound winding 242
On homopolar dynamos 477
Useful points in designing 367, 531, 588, 673, 702, 715
Utilization of copper, specific 368

V

Van Malderen's machine 10
Varley, Cromwell F. 174, 701
His transformer 701
Varley, C., and *S. A.*, self-exciting machine 12
Varley, S. Alfred, on compound winding 56
On homopolar dynamo 475
His machines 12
Varley, F. H., his machine 12
Varley, O., his machine 12
Ventilation of armatures .. 164, 292, 295, 373, 396, 403, 420, 452, 616, 623
Of field-magnets 373
Of transformers 708, 716, 717
Vertical-shaft dynamo 412
Vibration and noise 295, 777
"Victoria" dynamo 276, 285, 417
Vincent's multipolar drum 16
Virtual volts and amperes 553, 564
Voltage required in deposition 784
Volts lost in the armature 180
Volts, virtual 554
Volume of magnetizing coil 371
Volume (*see* Output).
Vulcanized fibre (*see* Insulating Materials)

W

Walenn, on reversibility of dynamo 18
Waltenhofen, on theory of dynamo 20
Warburg, on loss per magnetic cycle 135
Wasted power—In copper 347, 371, 761
In iron 137, 140, 347, 761
Waste of power at different current-densities 371
Waterhouse's regulator 747

PAGE
Watkins, his machine 8
Watt, the 200
Wattless current 567
Wattmeter 568
Wave form (*and see* Sine curve) 549, 552
Of transformer currents 712
Wave winding 596
Webber, on motor generators at Chelsea 725
Weber, on laws of induction 19
On theory of alternate currents 573
On unipolar induction 475, 478
Weber, H. F., on Lauffen transmission 742
Weber, the 144
Wedding, on alternate-current wave form 712
Weight of dynamos (*see also* Output), 405, 412, 416, 426, 429, 438, 444, 626
Of copper 416, 626
Weisbach, on power-measuring machines 755
Wenström—Dynamo, test of 764
Pierced core-disks 290
Westinghouse Co.—Air-blast for cleaning 771
Alternator 583, 602, 626, 638
Core-disks 288
Niagara alternators 638
Street-car motors 542, 544
Transformer 703, 714, 717
Weston's dynamos 16, 160
Wheatstone, Sir Charles—Motor 18
On self-exciting dynamo 13
Machines 9, 10
Use of electromagnets 9
Wheel dynamo 479
Wheeler, on parallel running 766
Whirls of magnetic lines 26
Widening of gap-space 379
Width of pole-faces (*see* Pole-pieces)
Wiener's data 339
Wilde's Alternator 580
Dynamos 10, 11, 16, 48, 469
Willan's Governor 748
High-speed engines 426, 434
Willesden paper (*see* Insulating materials).
Wilson, or retardation of magnetism 142
Winding of alternators 596
Of armatures 297
Of field-magnets 372, 607, 611, 621
Of Lauffen generator 630

PAGE
Winding of alternators—
  Of multiplex armatures .. 272
  Of polyphase motors .. 667, 673, 686
  Tables .. 247, 255, 260, 265, 268, 269, 629
  Of transformers .. 700, 715
  Relation of, to characteristic .. 207
  Triplex .. 273, 274
Wires (*see also* Binding wires *and* Cores) .. 776
Wire-wound armatures .. 298
Worms de Romilly, on drum winding .. 15
Wood's arc-light dynamo .. 465
Wood (*see* also Insulating materials)
  For distance pieces .. 286, 304, 307
  For wedges .. 602
  For driving horns .. 296
Woolrich's machine .. 8, 469
Work done by conductor in field .. 104, 486
  By motor .. 496, 501

Z

ZEUNER'S valve-gear diagram .. 551
Zickler, on compound winding .. 242
Zinc—Cost of, for motive power .. 485
  Use of, for footsteps .. 152, 354, 425
  " coil frames .. 612
Zipernowsky's Alternator .. 584, 611
  Transformer .. 702

LONDON: PRINTED BY WILLIAM CLOWES AND SONS, LIMITED, STAMFORD STREET
AND CHARING CROSS.

ON OF FIELD MAGNET.

le 1:8

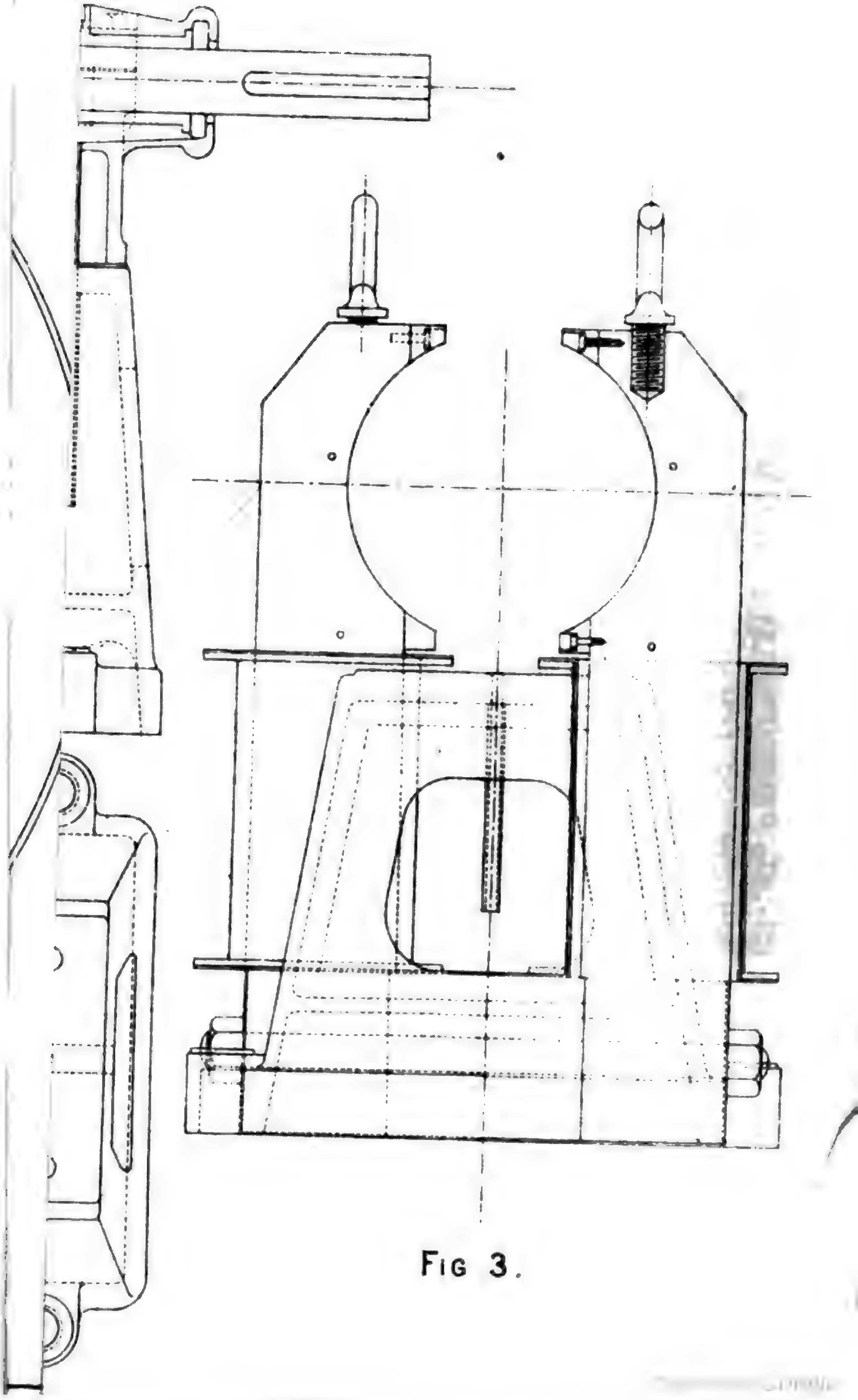


FIG 3.

ON OF FIELD MAGNET.

le 1:8

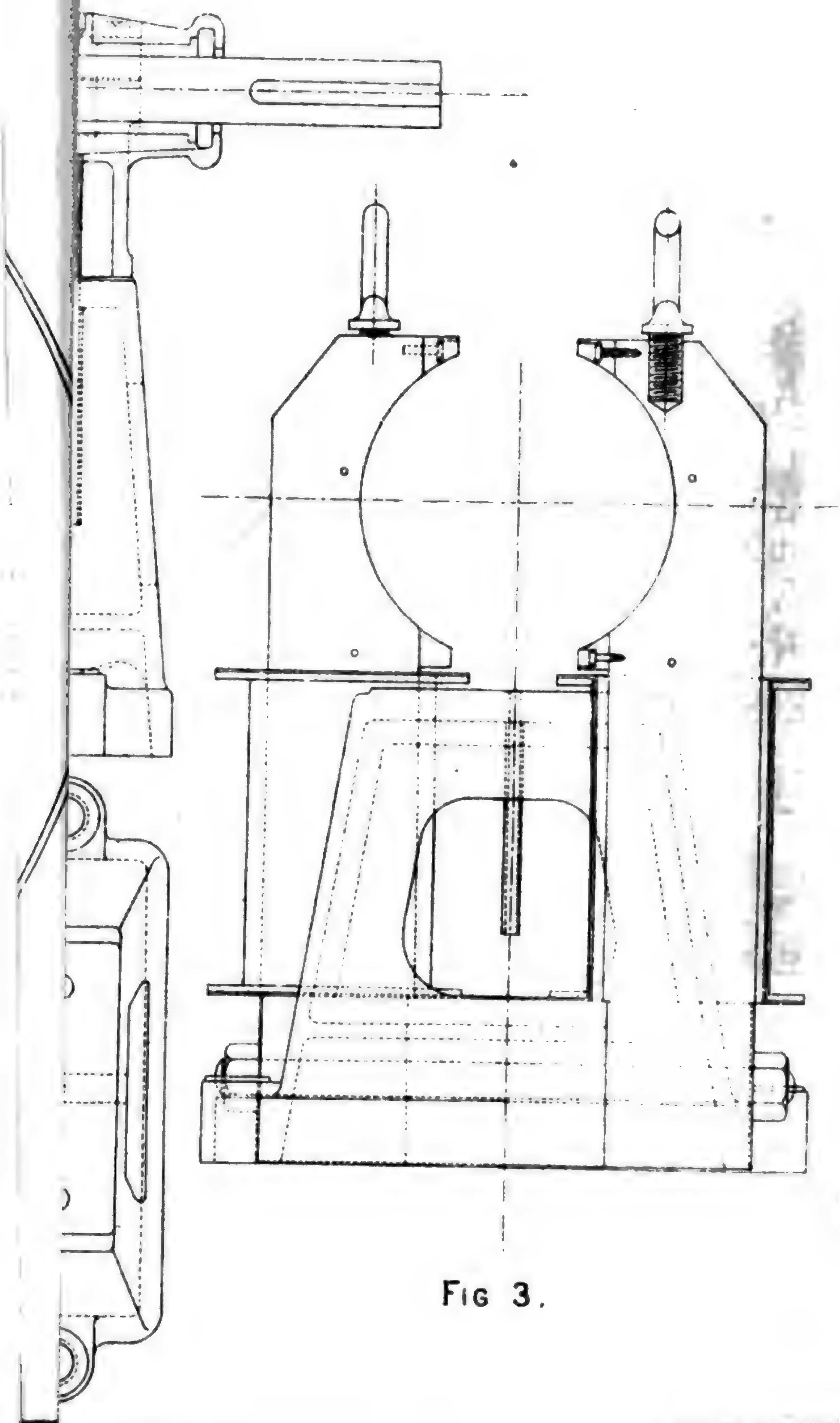


FIG 3.

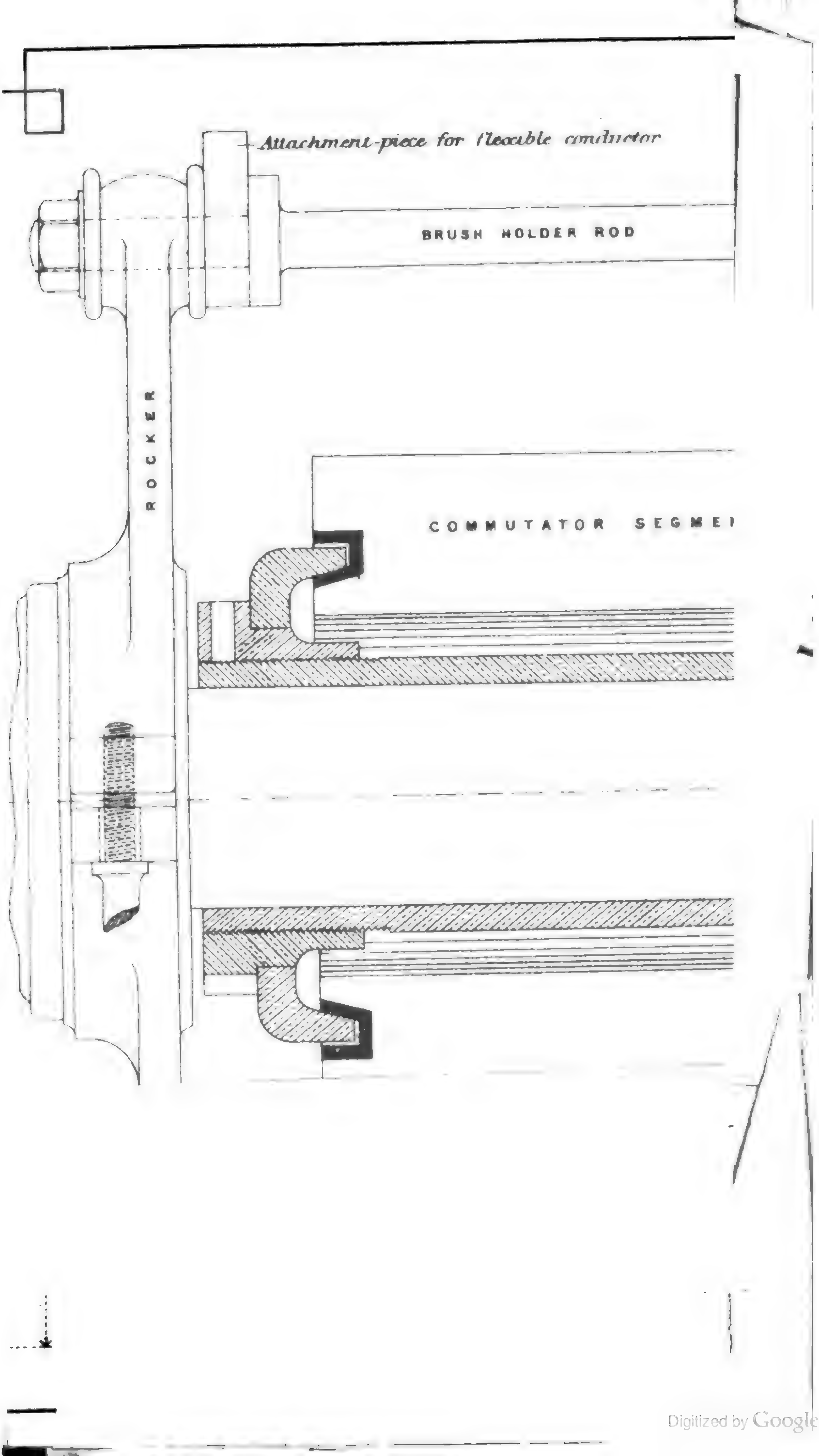
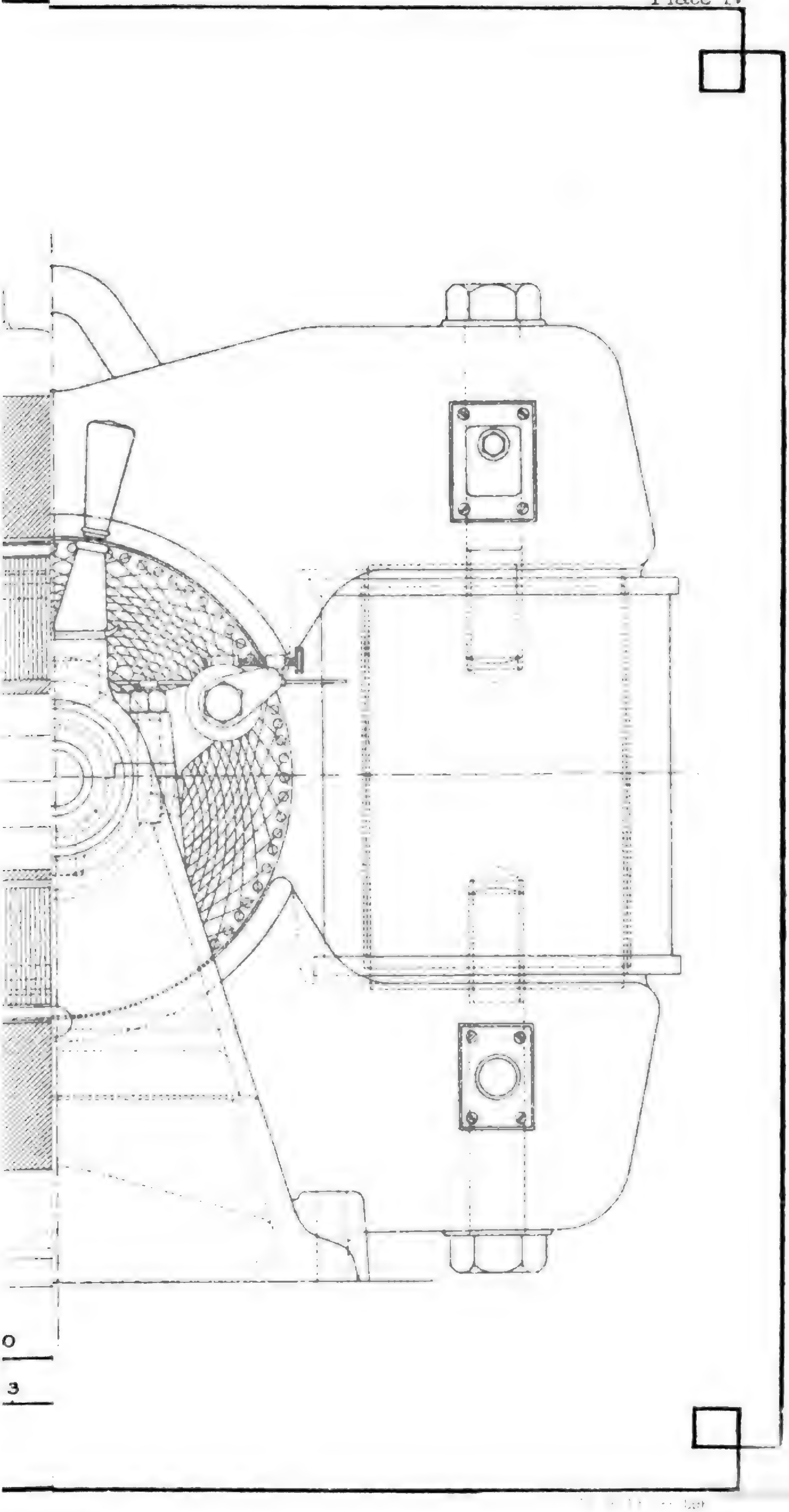

Attachment-piece for flexible conductor
BRUSH HOLDER ROD
ROCKER
COMMUTATOR SEGME

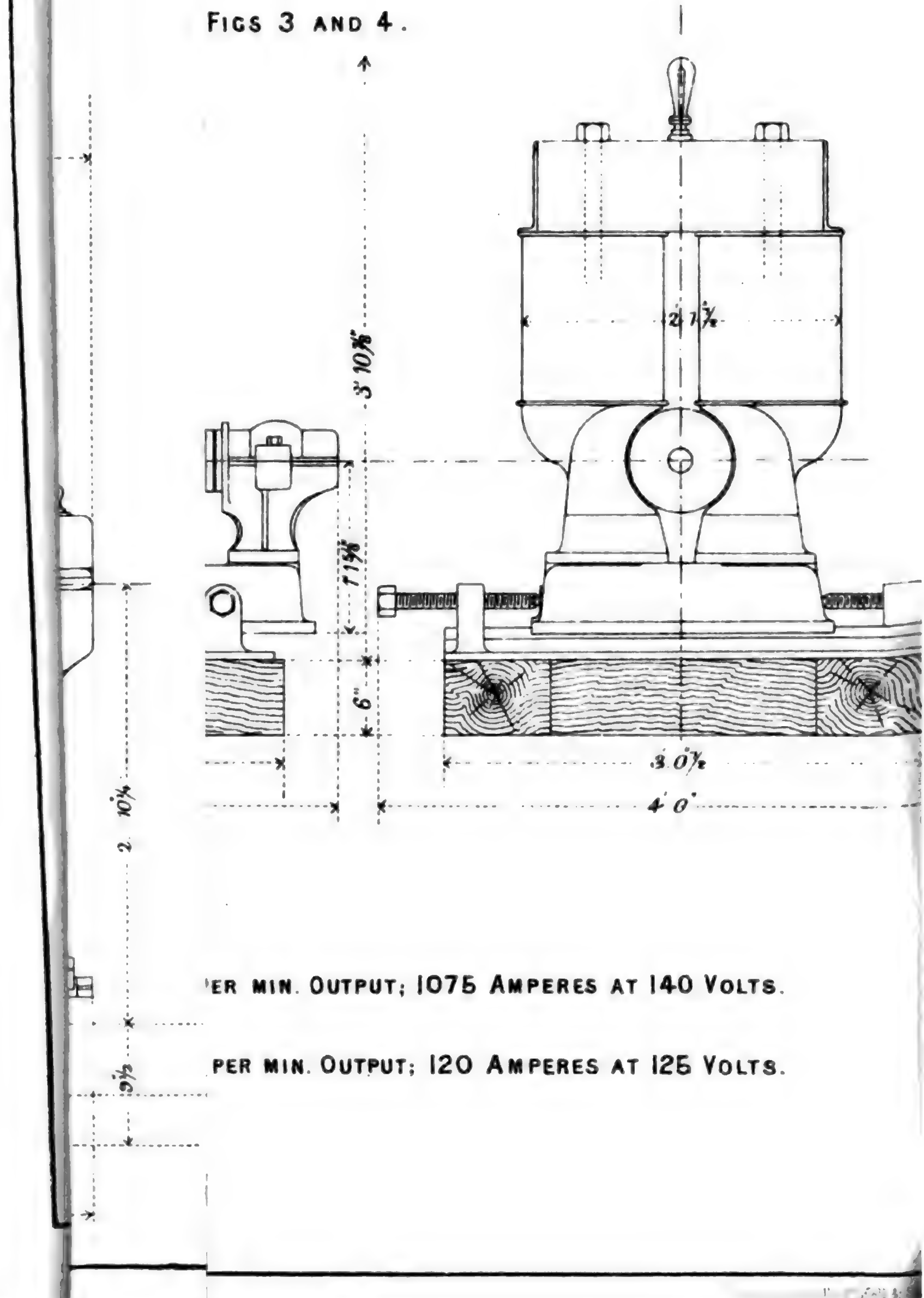
Plate IV



[E]DISON DYNAMOS.

[Ed]ison Machine Works, Schenectady, N.Y.

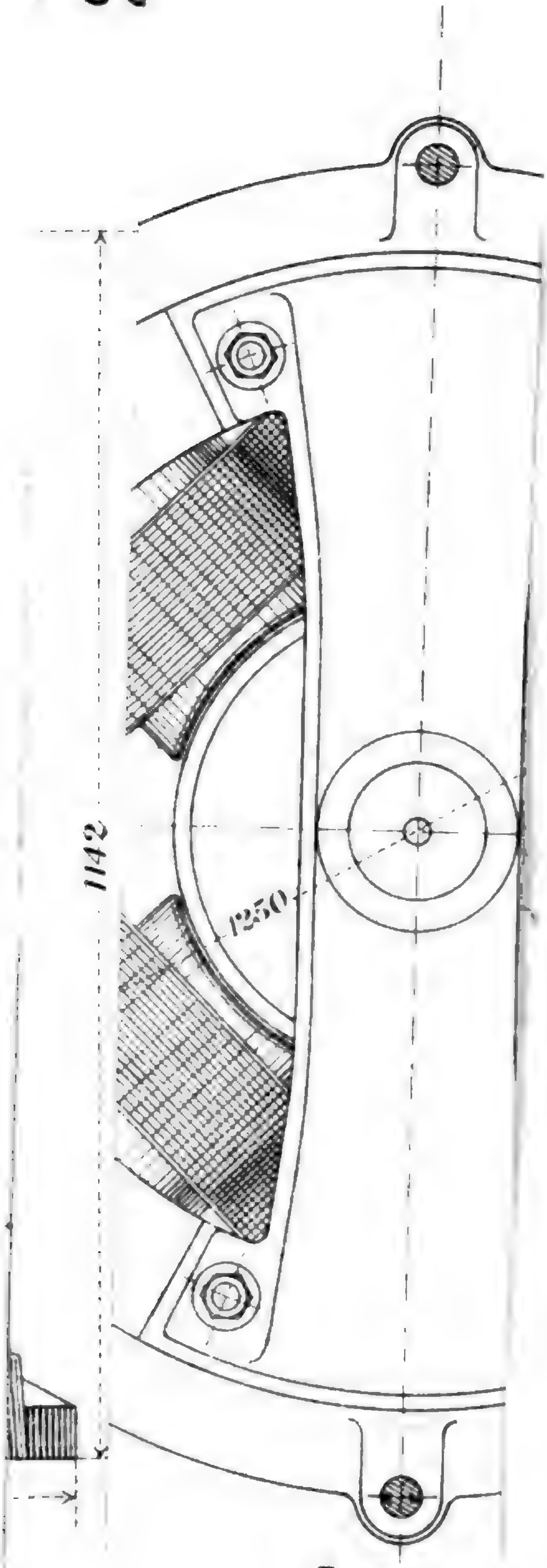
FIGS 3 AND 4.



[P]ER MIN. OUTPUT; 1075 AMPERES AT 140 VOLTS.

PER MIN. OUTPUT; 120 AMPERES AT 125 VOLTS.

3C·



PLAN

Scale

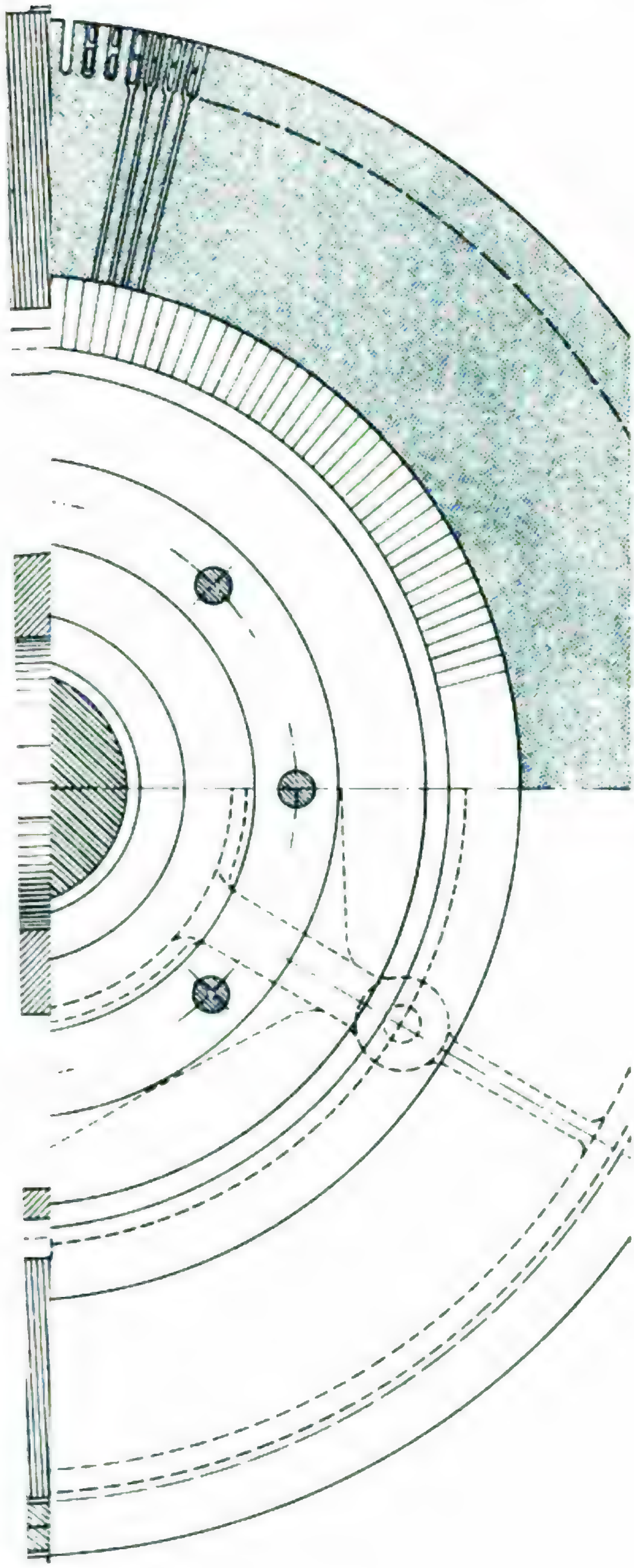
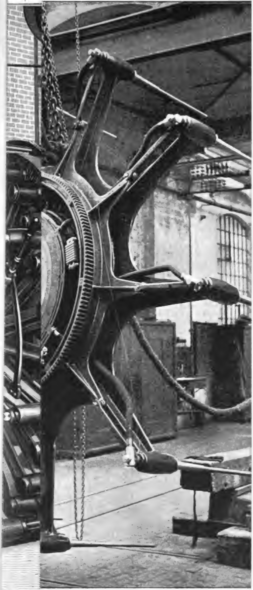
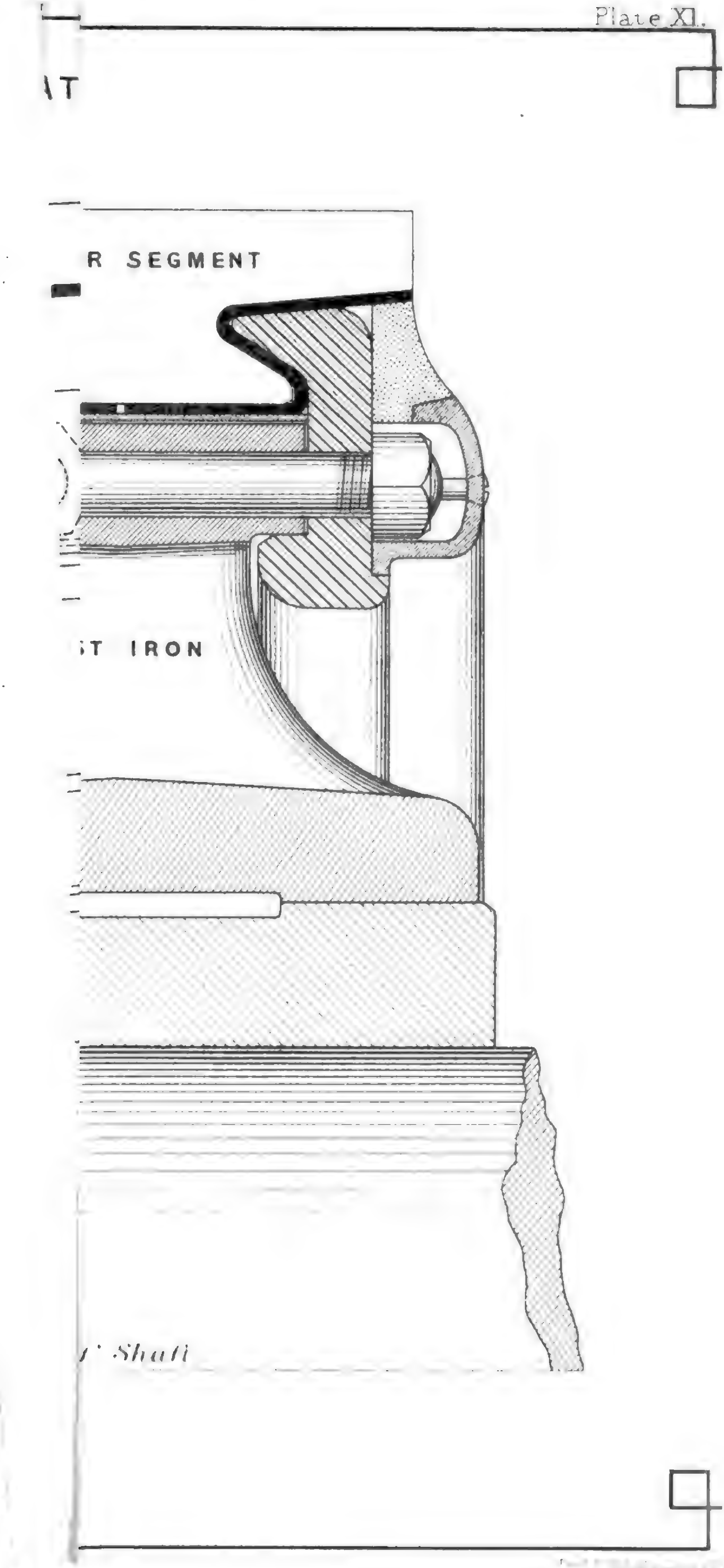
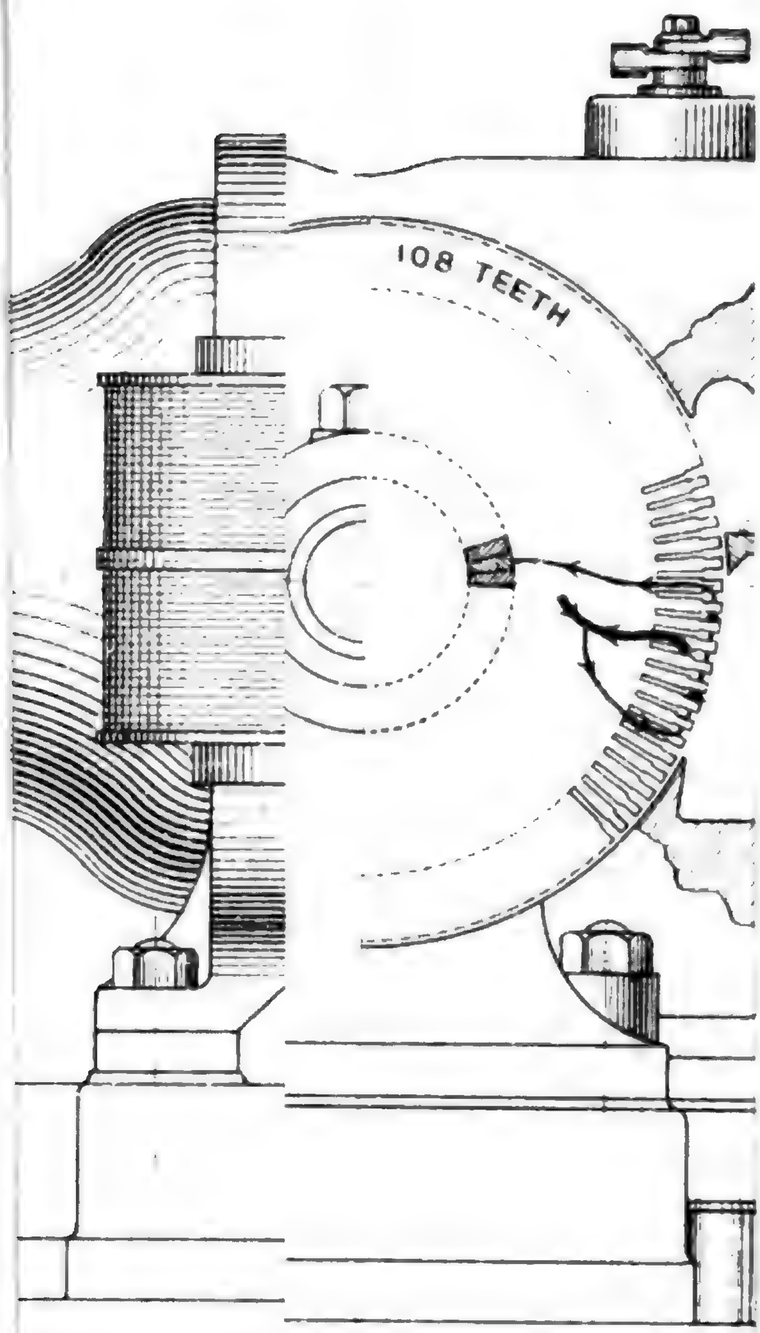


Plate VIII.



YNAMUSH-HOLDER RODS OF
AND HAN DYNAMO.


R SEGMENT
T IRON
Shaft

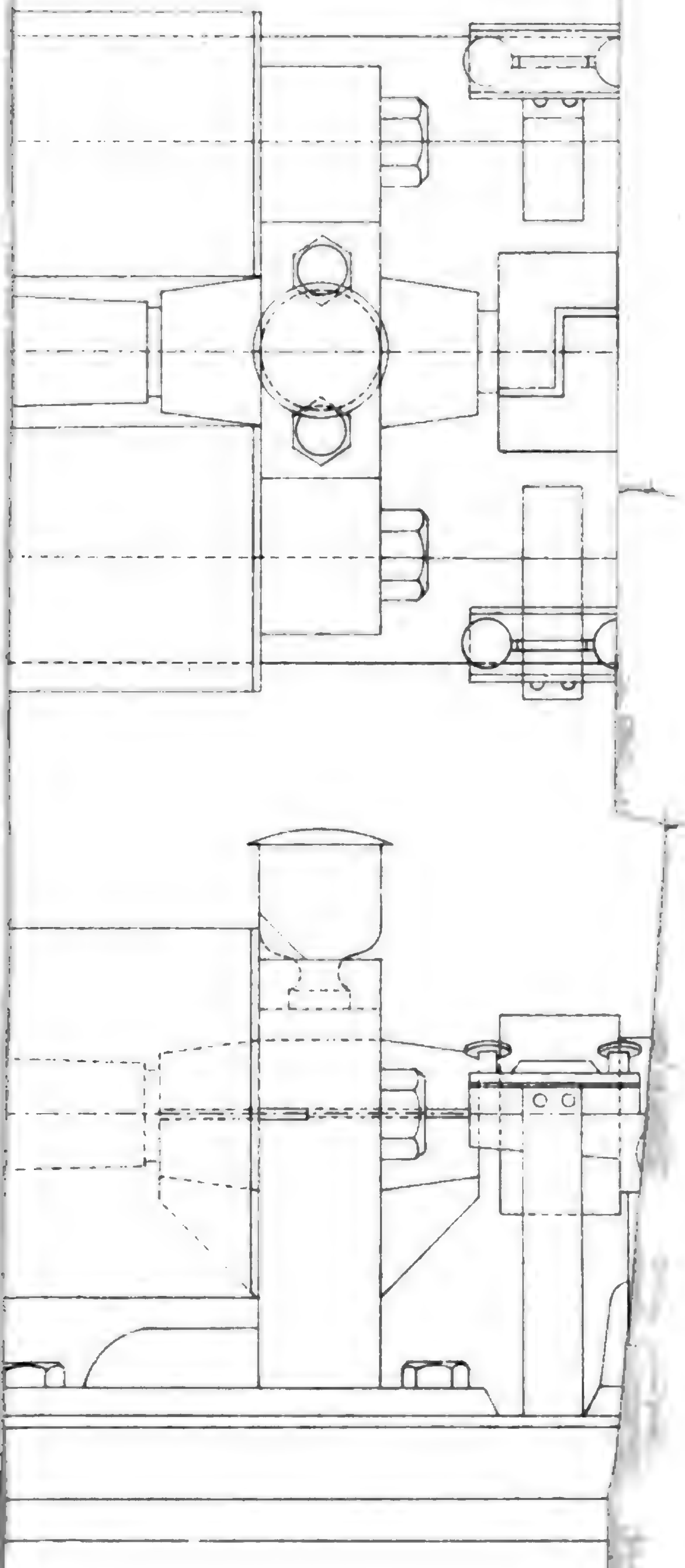


S

OUTPU

IGHT DYNAMO.
T 90 VOLTS.

H.



N

W YORK